Mars ISRU: State-of-the-Art and System Level Considerations

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"Addressing Mars ISRU Challenge"

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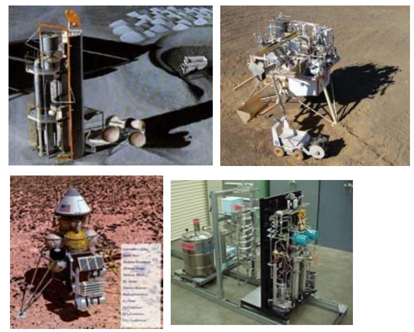
What is *In Situ* Resource Utilization (ISRU)?

ISRU involves any hardware or operation that harnesses and utilizes 'in-situ' resources to create products and services for robotic and human exploration

Resource Assessment (Prospecting)

Assessment of physical, mineral/ chemical, and volatile/ water resources, terrain, geology, and environment

Resource Processing/ Consumable Production



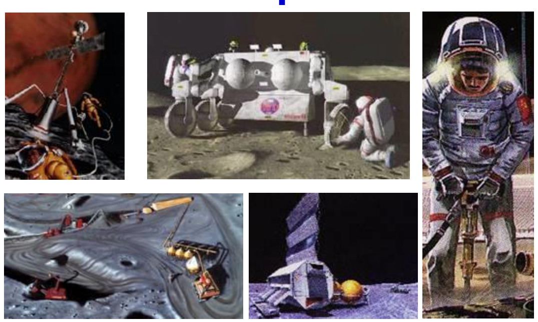
Processing resources into products with immediate use or as feedstock for construction and/or manufacturing

- Propellants, life support gases, fuel cell reactants, etc.

In Situ Manufacturing

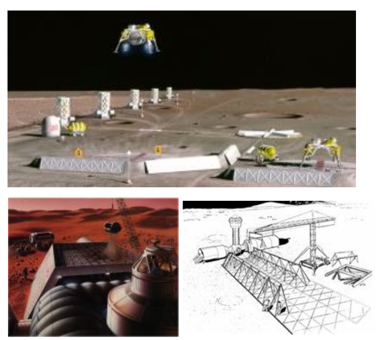
Production of replacement parts, complex products, machines, and integrated systems from feedstock derived from one or more processed resources

Resource Acquisition



Involves extraction, excavation, transfer, and preparation before processing

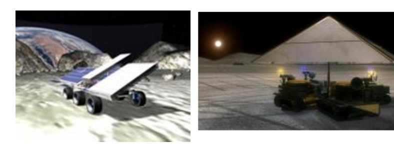
In Situ Construction



Civil engineering, infrastructure emplacement and structure construction using materials produced from in situ resources

- Radiation shields, landing pads, roads, berms, habitats, etc.

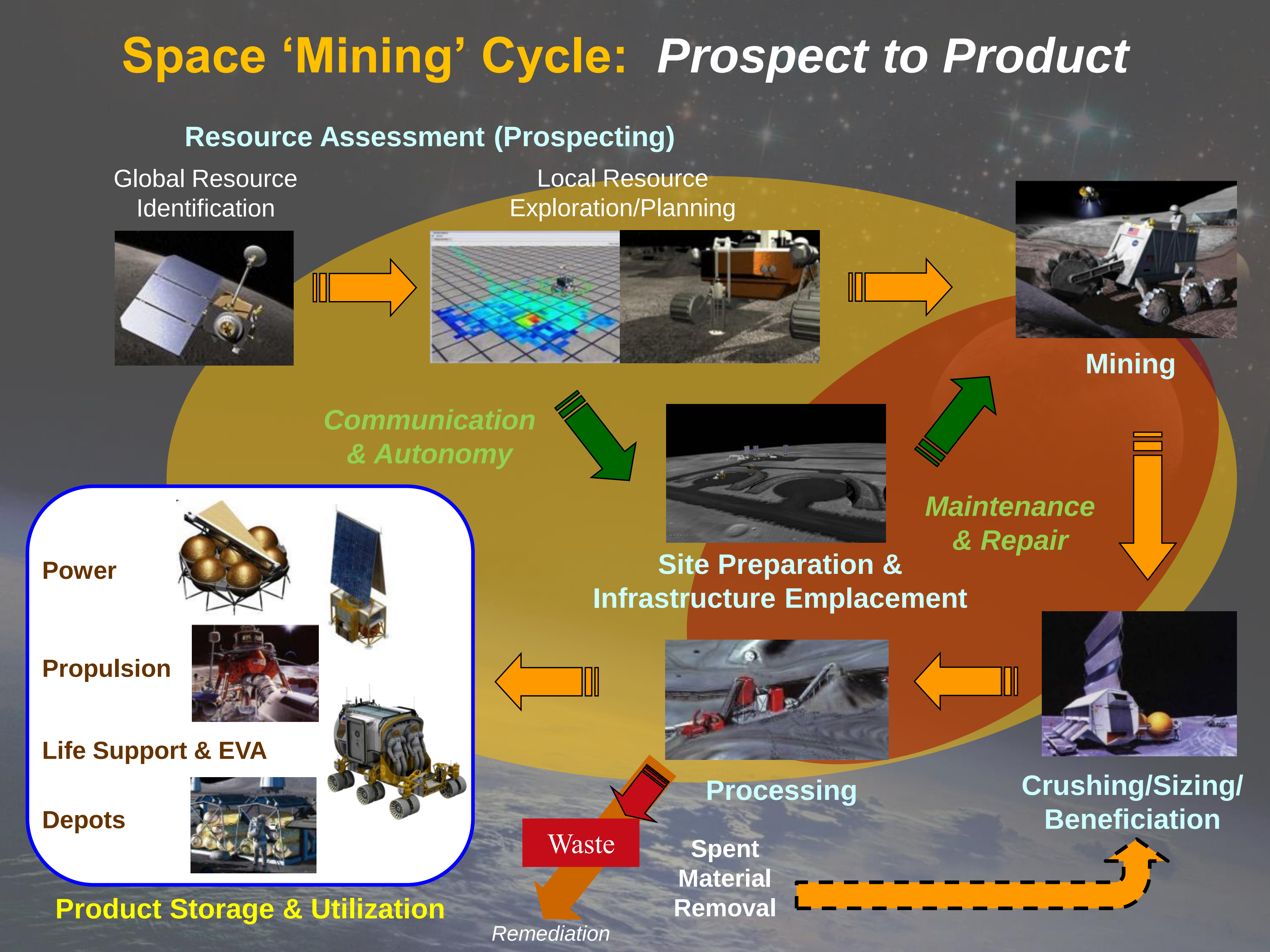
In Situ Energy



Generation and storage of electrical, thermal, and chemical energy with in situ derived materials

- Solar arrays, thermal wadis, chemical batteries, etc.

- **'ISRU' is a capability involving multiple elements to achieve final products** (mobility, product storage and delivery, power, crew and/or robotic maintenance, etc.)
- **'ISRU' does not exist on its own.** By definition it must connect and tie to users/customers of ISRU products and services



Space 'Mining' Cycle: Prospect to Product
Resource Assessment (Prospecting)
Global Resource Identification
Local Resource Exploration/Planning
Mining
Communication & Autonomy
Maintenance & Repair
Site Preparation & Infrastructure Emplacement
Power
Propulsion
Life Support & EVA
Depots
Product Storage & Utilization
Processing
Crushing/Sizing/ Beneficiation
Waste
Spent Material Removal
Remediation

Mars Resources

Atmosphere

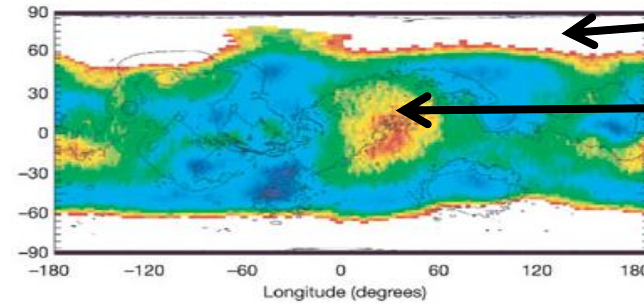
- Pressure: 6 to 10 torr (~0.08 to 0.1 psi);
- Temperature: +35 °C to -125 °C

Carbon Dioxide (CO_2)	95.32%
Nitrogen (N_2)	2.7 %
Argon (Ar)	1.6%
Oxygen (O_2)	0.13%
Water (H_2O)	0.08%
Carbon Monoxide (CO)	<0.03%

Soil/Minerals

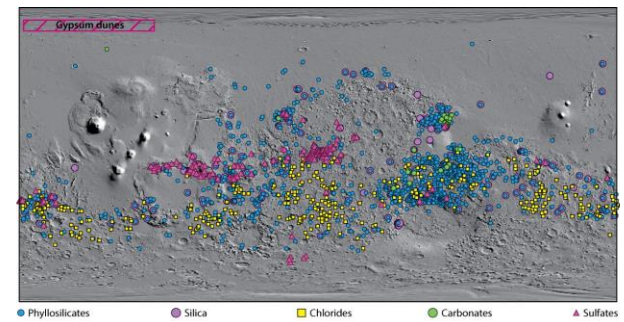
Resource	Potential Mineral Source
Water, Hydration/ Hydroxyl	Gypsum – ($CaSO_4.2H_2O$) Jarosite – ($KFe^{3+}_3(OH)_6(SO4)_2$) Opal & hydrated silica Phyllosilicates Other hydrated minerals (TBR)
Water, Ice	Icy soils Glacial deposits
Iron*	Hematite Magnetite Laterites
Aluminum*	Laterites Aluminosilicates Plagioclase Scapolite
Magnesium*	Mg-sulfates
Silicon	Pure amorphous silica Hydrated silica Phyllosilicates
Titanium*	Ilmenite

Water

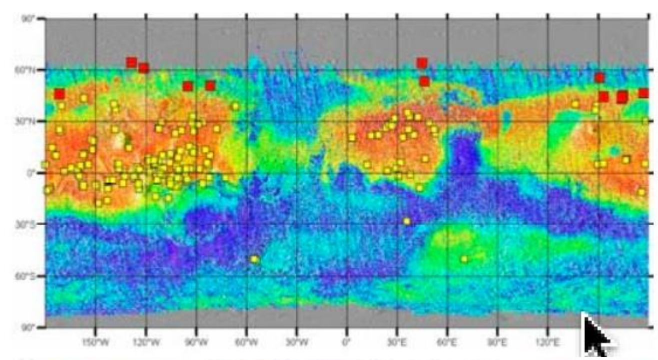


Mid- and high-latitude shallow ice

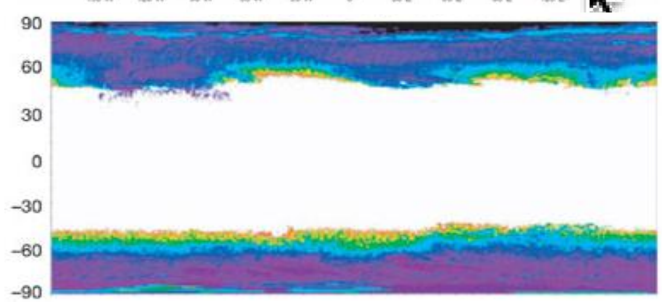
Thought to be dominated by **hydrated minerals**



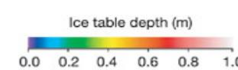
Map of **aqueous mineral** detections



New Craters Confirm Shallow, Nearly Pure Ice
Newly formed craters exposing water ice (red) are a subset of all new craters (yellow). Background color is TES dust index. (Adapted from Byrne et al. (2011) Science)



Ice in polar region

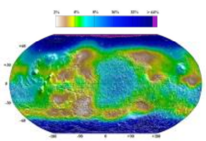


Mars ISRU Depends on Resource of Interest

Atmospheric Resource Processing

- **Strengths**
  - Atmospheric resources are globally obtainable (no landing site limitations)
  - Production of O_2 only from carbon dioxide (CO_2) makes >75% of ascent propellant mass
  - Significant research and testing performed on several methods of atmospheric collection, separation, and processing into oxygen and fuel; including life support development
- **Weaknesses**
  - Production of methane delivery of hydrogen (H_2) from Earth which is volume inefficient or water from the Mars soil (below)
  - Mars optimized ISRU processing does not currently use baseline ECLSS technologies

Mars Soil Water Resource Processing (ties to Lunar Ice & Regolith)



- **Strengths**
  - Surface material characteristics studied from Mars robotic landers and rovers
  - Water (in the form of hydrated minerals) identified globally near the surface
  - Lunar regolith excavation and thermal processing techniques can be utilized for Mars
  - Low concentrations of water in surface hydrated mineral soil (3%) still provides tremendous mass benefits with minimal planetary protection issues
- **Weaknesses**
  - Risk associated with the complexity of the required surface infrastructure needs must be evaluated. Significant autonomous operations required.
  - Local/site dependency on water resource concentration and form
  - Release of contaminants with water
  - Concerns from planetary protection and search for life with water extraction at higher concentrations

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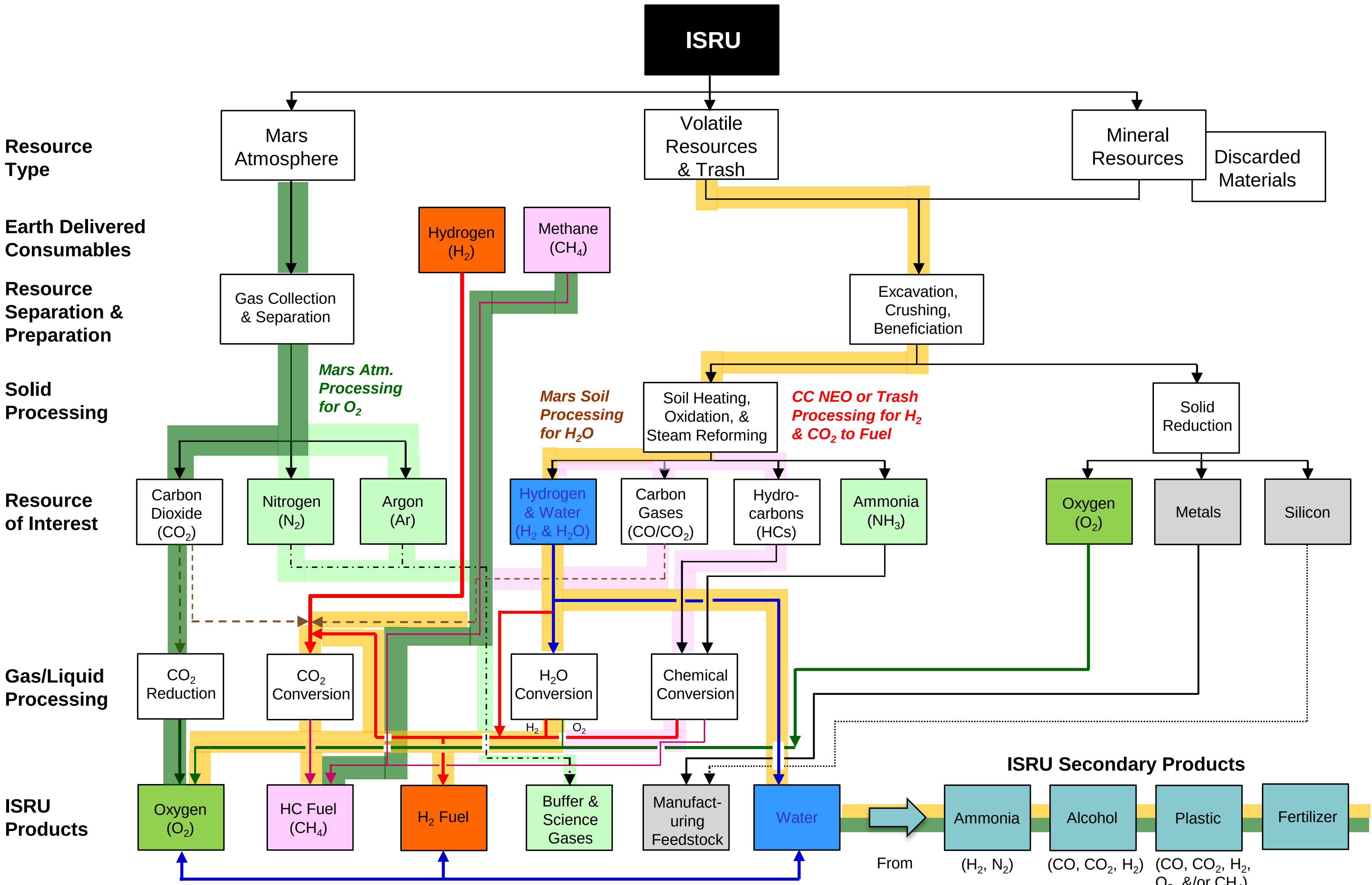
ISRU Consumables Production Decision Tree



ISRU Development and Implementation Challenges

Space Resource Challenges

- What resources exist at the site of exploration that can be used?
- What are the uncertainties associated with these resources?
- How to address planetary protection requirements?

ISRU Technical Challenges

- Is it technically feasible to collect, extract, and process the resource?
- How to achieve long duration, autonomous operation and failure recovery?
- How to achieve high reliability and minimal maintenance requirements?

ISRU Operation Challenges

- How to operate in extreme environments, including temperature, pressure, dust, and radiation?
- How to operate in low gravity or micro-gravity environments?

ISRU Integration Challenges

- How are other systems designed to incorporate ISRU products?
- How to optimize at the architectural level rather than the system level?
- How to manage the physical interfaces and interactions between ISRU and other systems?

Overcoming these challenges requires a multi-destination approach consisting of resource prospecting, process testing, and product utilization.

The Chemistry of Mars ISRU

2nd Step

Oxygen (O_2) Production Only

Zirconia Solid Oxide CO_2 Electrolysis (SOE)

$2\ CO_2 \xrightarrow{900 - 1000\ C} 2\ CO + O_2$ [Pt catalyst] → O_2

Reverse Water Gas Shift (RWGS)

$CO_2 + H_2 \overset{400 - 650\ C}{\rightleftharpoons} CO + H_2O$ [catalyst] → H_2O → WE to O_2

Bosch

$CO_2 + 2\ H_2 \xrightarrow{450 - 600\ C} C + 2\ H_2O$ [Ni, Ru, Fe, or Co catalyst] → H_2O → WE to O_2

Oxygen (O_2) & Methane (CH_4) Production

Sabatier Catalytic Reactor (SR)

$CO_2 + 4\ H_2 \overset{200 - 300\ C}{\rightleftharpoons} CH_4 + 2\ H_2O$ [Ru catalyst] → H_2O, CH_4 → WE to O_2

Methane Reformer

$CO + 3\ H_2 \xrightarrow{250\ C} CH_4 + H_2O$ [Ni catalyst] → H_2O, CH_4 → WE to O_2

Co-Production/Electrolysis

$CO_2 + 2\ H_2O \rightarrow CH_4 + 2\ O_2$ [Anode/Cathode] → O_2, CH_4

Other Hydrocarbon Fuel Production

Fischer-Tropsch (FT)

$n\ CO + (2n+1)\ H_2 \xrightarrow{>150\ C} C_nH_{2n+2} + n\ H_2O$ [catalyst] → H_2O, C_nH_{2n+2} → WE to O_2

Methanol

$CO + 2\ H_2 \xrightarrow[50 - 100\ atm]{250\ C} CH_3OH$ [ZnO catalyst] → CH_3OH

$CO_2 + 3\ H_2 \rightarrow CH_3OH + H_2O$ → H_2O, CH_3OH → WE to O_2

Oxygen (O_2) &/or Hydrogen (H_2) Production

Water Electrolysis (WE)

$2\ H_2O \rightarrow 2\ H_2 + O_2$ → O_2, $2\ H_2$

Steam Reforming

$H_2O + CH_4 \rightarrow 3\ H_2 + CO$ → $3\ H_2$

Dry Reforming

$CO_2 + CH_4 \rightarrow 2\ H_2 + 2\ CO$ → $2\ H_2$

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Mars Resource & ISRU Process Options

- **Four Options for Mars ISRU Ascent Propellant Production:**
  1. Make oxygen (O_2) from Mars atmosphere carbon dioxide (CO_2); Bring fuel from Earth
  2. Make O_2 and fuel/CH_4 from Mars atmosphere CO_2 and hydrogen (H_2) from Earth
  3. Make O_2 and fuel/CH_4 from Mars atmosphere CO_2 and water (H_2O) from Mars soil
  4. Make O_2 and H_2 from H_2O in Mars soil

	ISRU Resource Processing Options	ISRU Products	Mars Resource(s)	Earth Supplied		Process Subsystems/Options: CO_2 Collection & Conditioning	Solid Oxide CO_2 Electrolysis	Reverse Water Gas Shift (RWGS)	Sabatier	Bosch	Liquid Water Electrolysis	Solid Oxide H_2O Electrolysis	Ionic Liquid Electrolysis	Soil Processing	Soil Excavation & Delivery
Enabling	Atmosphere Processing	O_2	CO_2	CH_4 (~6600 kg)	1 a	X	X								
					b	X		X			X				
						X				X	X				
						X							X		
		O_2, CH_4, H_2O		H_2* (~2000 kg)		X	X		X			X			
					2	X		X	X		X				
						X							X		
Enabling or Enhancing	Soil Processing	O_2, CH_4, H_2O	H_2O	CH_4 **(~6600 kg)							X			X	X
	Atmosphere & Soil Processing	O_2, CH_4, H_2O	CO_2 & H_2O		3	X			X		X			X	X
						X			X			X		X	X

*H_2 for water and methane production

**Assumes methane fuel vs hydrogen fuel for propulsion

1, 2, & 3 Were Evaluated in Mars DRA 5.0

Mars Human Exploration DRA 5.0
ISRU vs Non-ISRU Ascent Results

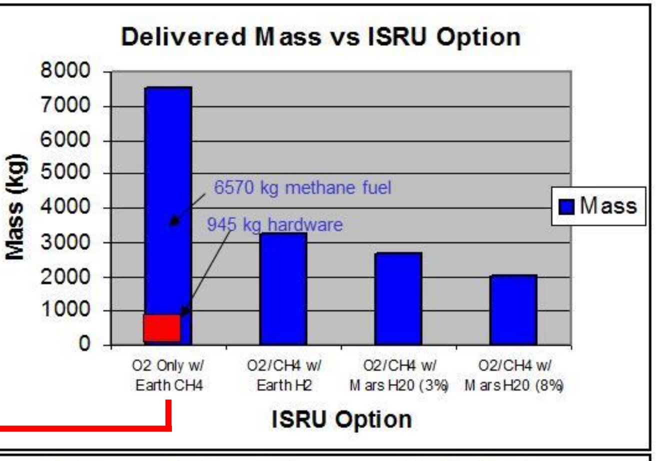
- **Lowest Power/Volume**: Process atmospheric CO_2 into O_2; Bring methane (CH_4) from Earth
- **Lowest Mass**: Process atmospheric CO_2 with Soil processing for H_2O into O_2 and CH_4
- Study Results
  - Atmosphere processing into O_2 baselined: **Lowest Risk**
  - Continue evaluation of water on Mars and soil processing to reduce risk

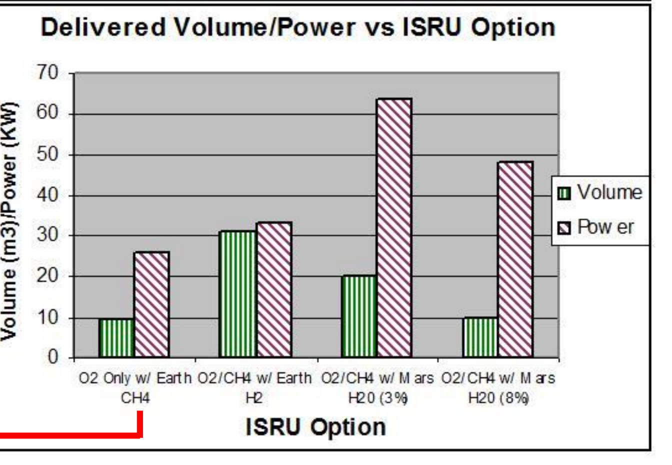
DAV Mass (no ISRU)		
Ascent Stg 2	18,540	kg
Ascent Stg 1	27,902	kg
Minimal Habitat†	5687	kg
Descent stage*	27,300	kg
Total	79,428	kg

*** Wet mass; does not include EDL System**

† Packaging not currently considered

DAV Mass (w/O2 ISRU)		
Ascent Stg 2	9,330	kg (CH4)
Ascent Stg 1	12,156	kg (CH4)
ISRU and Power†	11280	kg
Descent stage*	21,297	kg
Total	54,062	kg





>25 MT savings (>30%)

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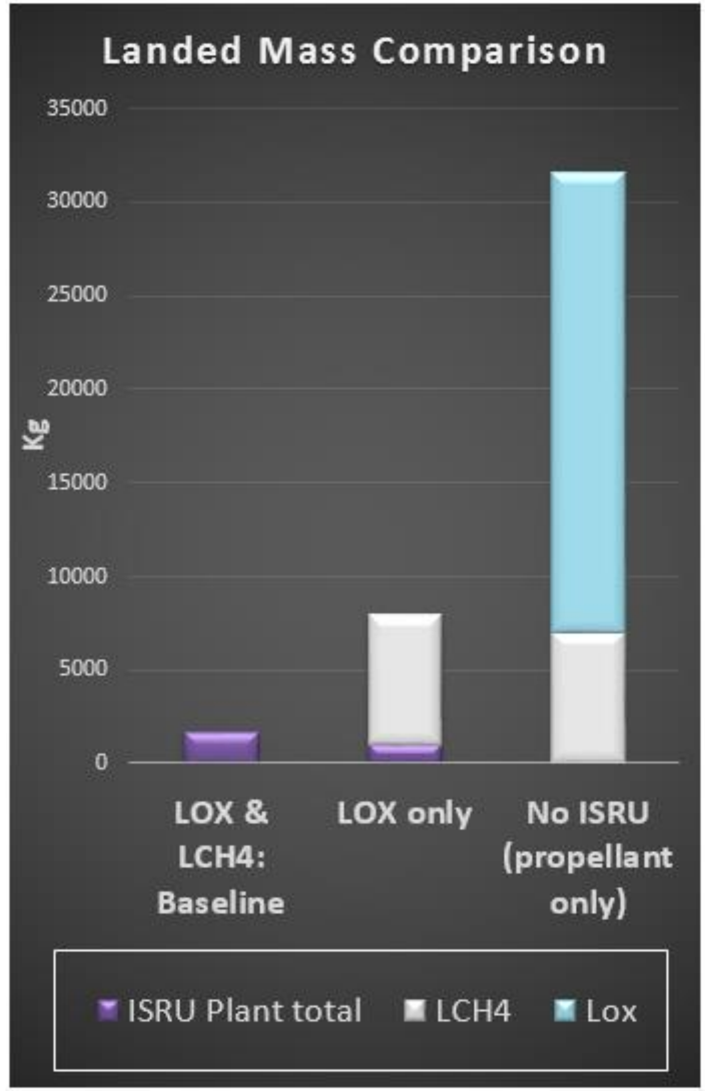
ISRU system Mass Comparison

The ISRU system leverages the power and radiator systems that are pre-positioned by the lander for human systems. So these are not explicitly part of the ISRU system.

	Hardware Mass, mt	Total Mass, mt (ISRU Hardware + Propellant from Earth)	Ratio: Propellant produced per kg of landed mass
Case 1 ISRU for LO_2 & LCH_4: Sulfates	1.6	1.6	22.1
Case 2 ISRU for LO_2 & LCH_4: Regolith	1.7	1.7	20.5
Case 3 ISRU for LO_2 only (no water)	1.0	8.0 (1mt hardware + 7mt Methane)	3.1
Case 4 Propellant only (no ISRU)	NA	31.6 (24mt Oxygen + 7mt Methane)	NA

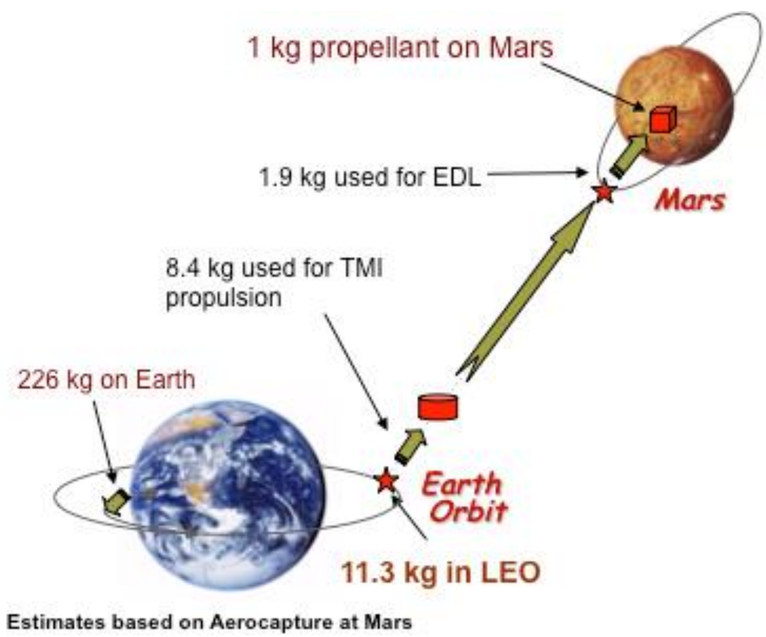


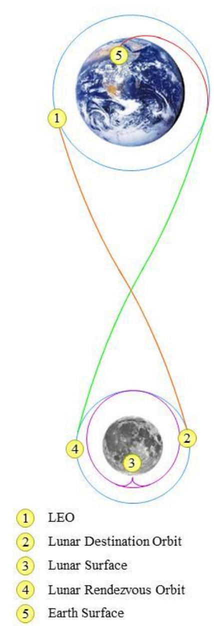
How Propellant Production Enables Future Moon & Mars Missions

Every 1 kg of propellant made on the Moon or Mars saves 7.4 to 11.3 kg in LEO

Potential 340 mT launch mass saved in LEO = 3 to 5 SLS launches avoided per Mars Ascent

- **Mars mission**
  - Oxygen only — 75% of ascent propellant mass: ~ 23 mT
  - Methane + Oxygen — 100% of ascent propellant mass: ~ 30 mT
    Regeneration of rover fuel cell reactant mass





A Kilogram of Mass Delivered Here…	…Adds This Much Initial Architecture Mass in LEO	…Adds This Much To the Launch Pad Mass
Ground to LEO	-	20.4 kg
LEO to Lunar Orbit (#1→#2)	4.3 kg	87.7 kg
LEO to Lunar Surface (#1→#3; e.g., Descent Stage)	7.5 kg	153 kg
LEO to Lunar Orbit to Earth Surface (#1→#4→#5; e.g., Orion Crew Module)	9.0 kg	183.6 kg
Lunar Surface to Earth Surface (#3→#5; e.g., Lunar Sample)	12.0 kg	244.8 kg
LEO to Lunar Surface to Lunar Orbit (#1→#3→#4; e.g., Ascent Stage)	14.7 kg	300 kg
LEO to Lunar Surface to Earth Surface (#1→#3→#5; e.g., Crew)	19.4 kg	395.8 kg

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Why Methane Fuel?

- **Simplicity of ISRU Processing**
  - Single step process for methane.
    - Two or more steps for most other hydrocarbon fuels
  - High processes conversion:
    - >99% methane product from CO_2 in single pass (recycle H_2)
    - Other fuels (such as Fischer Tropsch) have wide band of hydrocarbons produced; must separate and recycle (increase complexity), or accept (decrease in engine performance)

- **Higher propulsion efficiency**
  - Pros: Higher Isp than most other hydrocarbons
    High ox/fuel (O/F) mixture ratio. (Max. benefit for O_2 only ISRU)
    Clean burning; no coking
  - Cons: Methane is lower density than other hydrocarbons
    High H-to-C ratio (Min. benefit for Earth provided H_2 ISRU options)

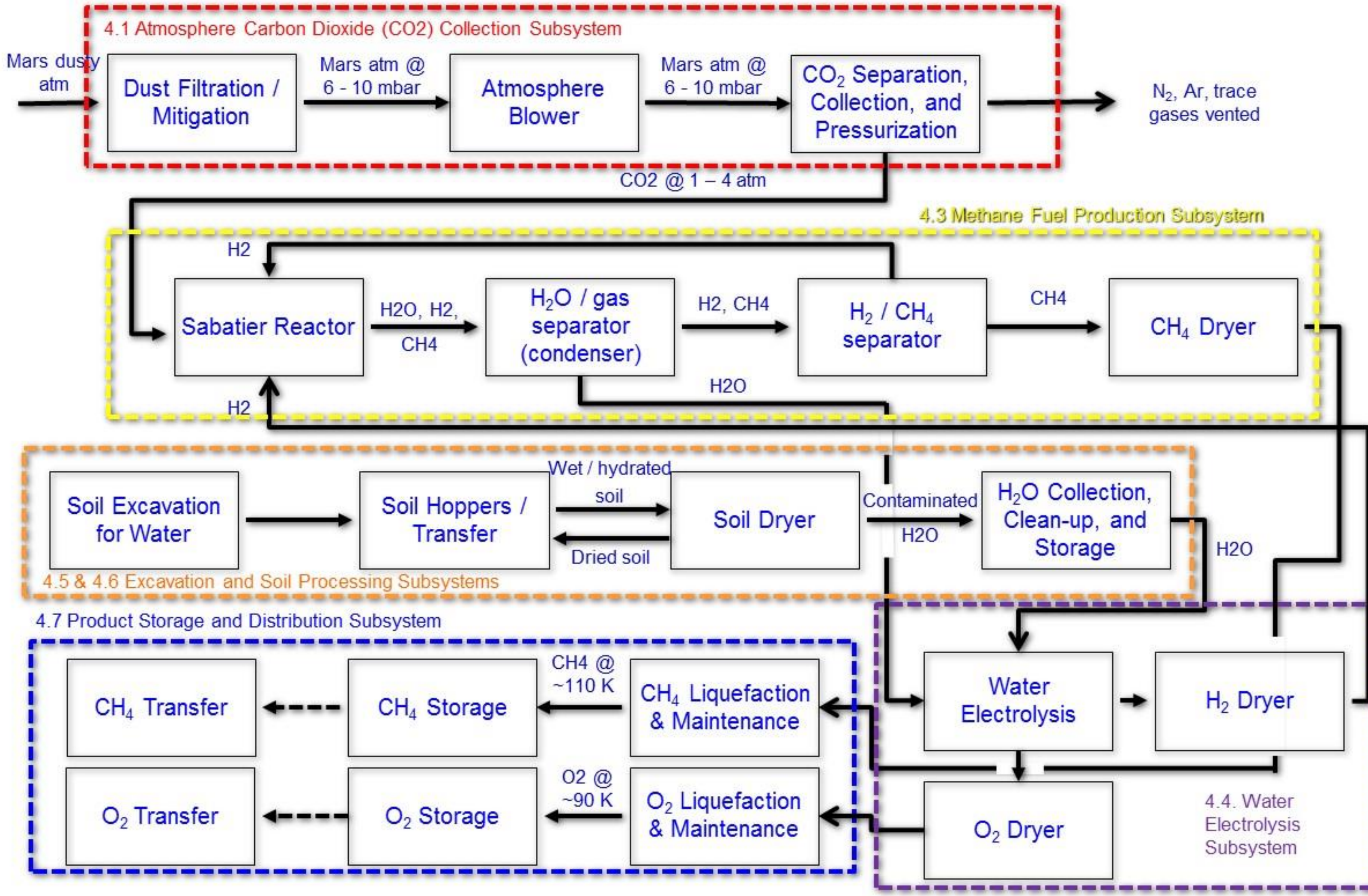
	NTO/MMH Press-fed	LO_2/Hydrazine Press-fed	LO_2/Methane Press-fed	LO_2/Propane Press-fed	LO_2/Methanol Press-fed	LO_2/Ethanol Press-fed	LO_2/Ethylene Press-fed	LO_2/Kerosine Press-fed	LO_2/LH_2 Press-fed	LO_2/LH_2 Pump-fed
Isp	328	365	362	357	335	340	364	352	441	454
MR	1.9	1.0	3.5	3.25	1.5	2	2.75	3.0	5.25	6.0
Fuel Density (kg/m^3)	880	1020	422	500-580	792	789	568	810	71	71
Fuel B.P (K)	360	387	111.7	230.9	337.8	351.5	169.5		20.3	20.3

Based on Chamber Pressure (Pc) = 500 psi; Area Ratio (AR)=150:1; Efficiency = 93%

- **Higher compatibility with liquid oxygen**
  - Same technology, insulation, cryocoolers, and tanks used for CH_4 as with LO_2
  - Thermal compatibility of lines and engine/thruster thermal management

Overall, choice of methane fuel is an overall balance of performance, storage, compatibility, and production

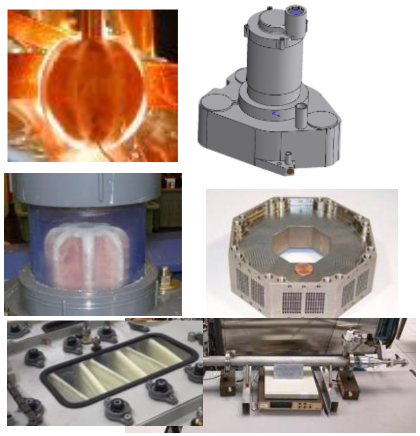
ISRU Fuel and Oxygen Production End-to-End Integrated System (PEM Based)



Each Function influences the design & operation of connecting boxes

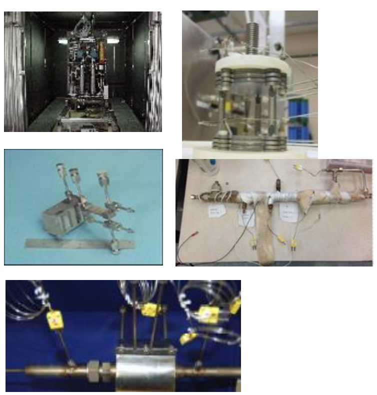
You can't optimize a single functional box; You need to optimize the system

Past/Recent Mars ISRU Technology Development



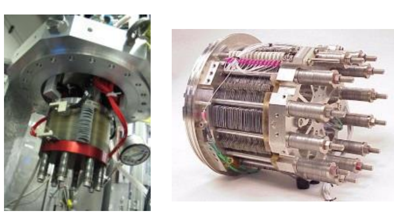
CO_2 Collection & Separation

- Mars dust filtration – filter, electrostatic, cyclone (GRC, KSC, JPL, SBIR)
- Mars atmosphere adsorption pump - Day/Night (LMA, JPL, ARC, JSC)
- Microchannel rapid-cycle adsorption pump (PNNL, SBIR)
- Mars atmosphere solidification (CO_2 freezing) pump (LM, SBIR, KSC)
- Mars atmosphere compressor (MOXIE/SBIR)
- Ionic liquids adsorption/electrochemistry (MSFC, SBIRs)



CO_2 Processing

- Solid Oxide CO_2 Electrolysis (NASA, Universities, Industry, SBIRs)
- Low pressure CO_2 Glow/Plasma Dissociation (Universities)
- Reverse Water Gas Shift (KSC, PNNL, SBIRs)
- Sabatier reactors (NASA, Industry, SBIRs)
- Bosch/Boudouard reactors – MSFC, KSC, Industry, Univ., SBIRs
- Methane reformer (JPL, SBIRs)
- Hydrocarbon fuel reactors - methanol, toluene, ethylene, etc. (SBIRs)
- Microchannel chemical reactors/heat exchangers (PNNL, SBIRs)
- ElectrolysisCo-Production O_2/Fuel – PEM and Ionic Liquids (MSFC/KSC, SBIRs)



Water Processing

- Water electrolysis/decomposition (NASA, Industry, SBIRs)
- PEM-High and Low Pressure & Solid Oxide (NASA, Industry, SBIRs)
- Water separation/collection – membrane & cooling (NASA, Industry)

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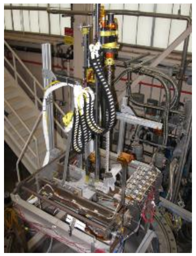
Past/Recent Mars ISRU Technology Development



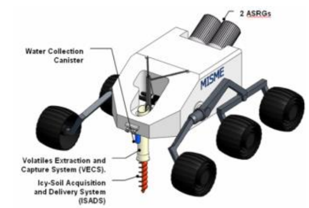


Soil Acquisition and Excavation

- Sample drills and augers (JPL, ARC, SBIRs)
- Scoops and buckets (GRC, KSC, JPL, Univ., SBIRs)
- Auger and pneumatic transfer (KSC, GRC, SBIRs)



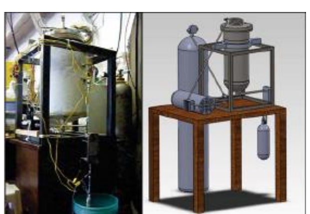







Soil Processing

- H_2 Reduction of regolith reactors (NASA, LMA)
- Microwave soil processing (MSFC, JPL, SBIR)
- Open and closed Mars soil processing reactors (JSC, GRC, SBIRs)
- Downhole soil processing (MSFC, SBIRs)
- Capture for lunar/Mars soil processing (NASA, SBIRs)
- Water cleanup for lunar/Mars soil processing (KSC, JSC, SBIRs)



Trash/Waste Processing into Gases/Water

- Combustion, Pyrolysis, Oxidation/Steam Reforming (GRC, KSC, SBIRs)

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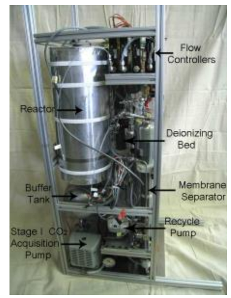
Past/Recent Mars ISRU System Development

Mars Atmosphere Processing

- 1st Gen Sabatier/Water Electrolysis (SWE) breadboard under ambient & Mars environment testing in late '90s/early 00's (NASA, Lockheed Martin)
- 1st Generation Reverse Water Gas Shift with and w/o Fuel production (NASA, Pioneer Astronautics)

Sabatier/Water Electrolysis w/ CO_2 Absorption (LMA & JSC) *[Tested under simulate Mars surface conditions]*

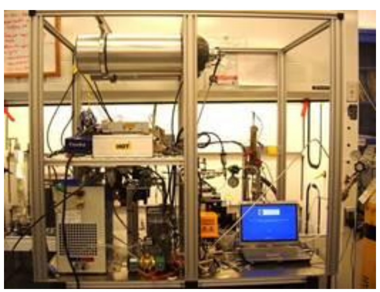


Combined Sabatier/ RWGS/Water Electrolysis (Pioneer Ast.)

CO_2 Electrolysis (GRC) *[Tested under conference conditions]*

Reverse Water Gas Shift/ Water Electrolysis (KSC & Pioneer Astrobotics)

- 2nd Gen MARCO POLO atmosphere processing (JSC, KSC)



Atm Processing Module
0.088 kg/hr CO_2
0.033 kg/hr CH_4
0.071 kg/hr H_2O

Water Processing Module
0.52 kg/hr H_2O
0.46 kg/hr O_2
0.058 kg/hr H_2

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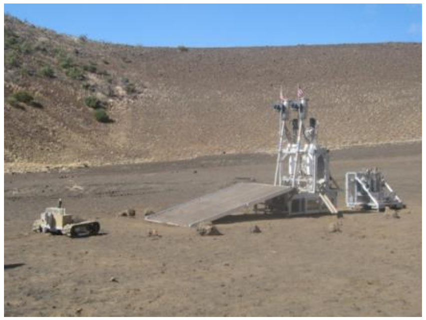
Past/Recent Mars ISRU System Development

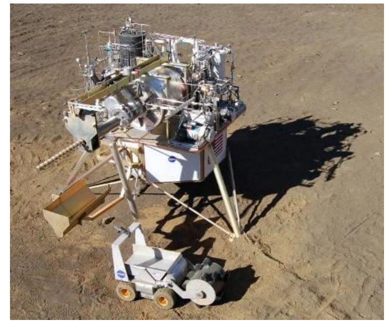
Lunar/Mars Soil Processing

- 1st Gen H_2 Reduction from Regolith Systems (NASA, LMA)



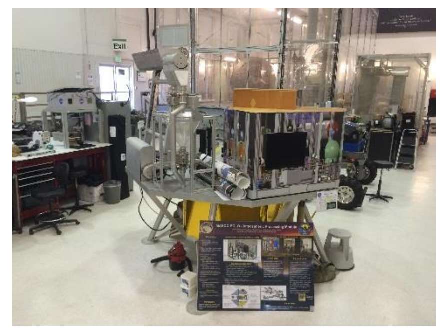
ROxygen H_2 Reduction
Water Electrolysis
Cratos Excavator

PILOT H_2 Reduction
Water Electrolysis
Bucketdrum Excavator



- 2nd Gen MARCO POLO soil processing system (JSC, KSC)

Soil Processing Module
10kg per batch; 5 kg/hr
0.15 kg/hr H_2O
(3% water by mass)



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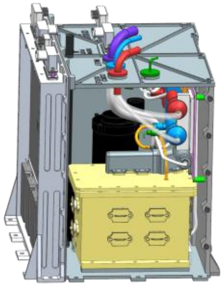
Current ISRU Missions

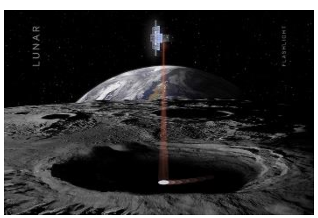


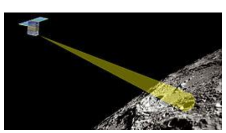
Mars 2020 ISRU Demo

- Make O2 from Atm. CO_2: ~0.01 kg/hr O_2; <600 W-hrs; >10 sols of operation
- Scroll Compressor and Solid Oxide Electrolysis technologies
- Payload on Mars 2020 rover

Resource Prospector – RESOLVE Payload

- Measure H_2O: Neutron spec, IR spec., GC/MS
- Measure volatiles – H_2, CO, CO_2, NH_3, CH_4, H_2S: GC/MS
- Possible mission in 2020





Orbiters/Cubesats

- Lunar Flashlight: Use laser and spectrometer to look into shadowed craters for volatiles
- Lunar Ice Cube: Broadband InfraRed Compact High Resolution Explorer Spectrometer (BIRCHES) instrument
- Skyfire: Spectroscopy and thermography for surface characterization
- Mars 2022 Orbiter: Radar for ground ice and spectrometers for hydrated minerals

Mars ISRU Propellant Production

Large Gap between Needs and Demonstrated

Needs

- **Propellant production for human mission ascent (Mars DRA 5.0)**
  - For O_2 only: 2.2 to 3.5 kg/hr O_2; 480 days or 300 days
  - For O_2/CH_4:
    - 0.55 to 0.88 kg/hr CH_4
    - 1.2 to 2.0 kg/hr H_2O; (41 to 66 kg/hr soil @ 3% H2O by mass)

- **Propellant production for Mars Sample Return**
  - 0.35 to 0.5 kg/hr O_2; 420 to 500 days (multiple studies)
  - 0.75 to 1.5 kg/hr O_2; 35 or 137 days (Mars Collaborative Study 4-2012)

- **Propellant production for Mars ISRU Demo**
  - 0.02 kg/hr O_2; 50 operations (Mars 2020 AO requirement)
  - 0.00004 kg/hr O_2; 10 operations (MIP demo on Mars 2001 Surveyor)

Demonstrated

- **Mars ISRU Testbeds (late '90s early '00s):**
  - LMA/JSC Sabatier/Water Electrolysis: 0.02 kg/hr O_2; 0.01 kg/hr CH_4
  - KSC RWGS/Water Electrolysis 0.087 kg/hr O_2
  - Pioneer Astronautics (SWE & RWGS): 0.02 kg/hr O_2; 0.01 kg/hr CH_4
    (IMISPPS): 0.031 kg/hr O_2, 0.0088 kg/hr CH_4

- **Atmosphere Processing: MARCO POLO** (Individual subsystems)
  - CO_2 Collection: 0.088 kg/hr CO_2
  - CO_2 Processing: 0.066 kg/hr of O_2; 0.033 kg/hr of CH_4; 0.071 kg/hr of H_2O
  - Water Processing: 0.52 kg/hr H_2O; 0.46 kg/hr O_2

- **Soil Processing:**
  - Lunar H_2 Reduction - ROxygen Reactor: 5 to 10 kg/hr soil:
  - Lunar H_2 Reduction - PILOT Reactor: 4.5 to 6 kg/hr soil:
  - Mars Soil Auger - MISME: 0.18 to 0.2 kg/hr soil
  - Mars Soil Reactor-Pioneer Ast. Hot CO_2 4 kg/hr soil per batch

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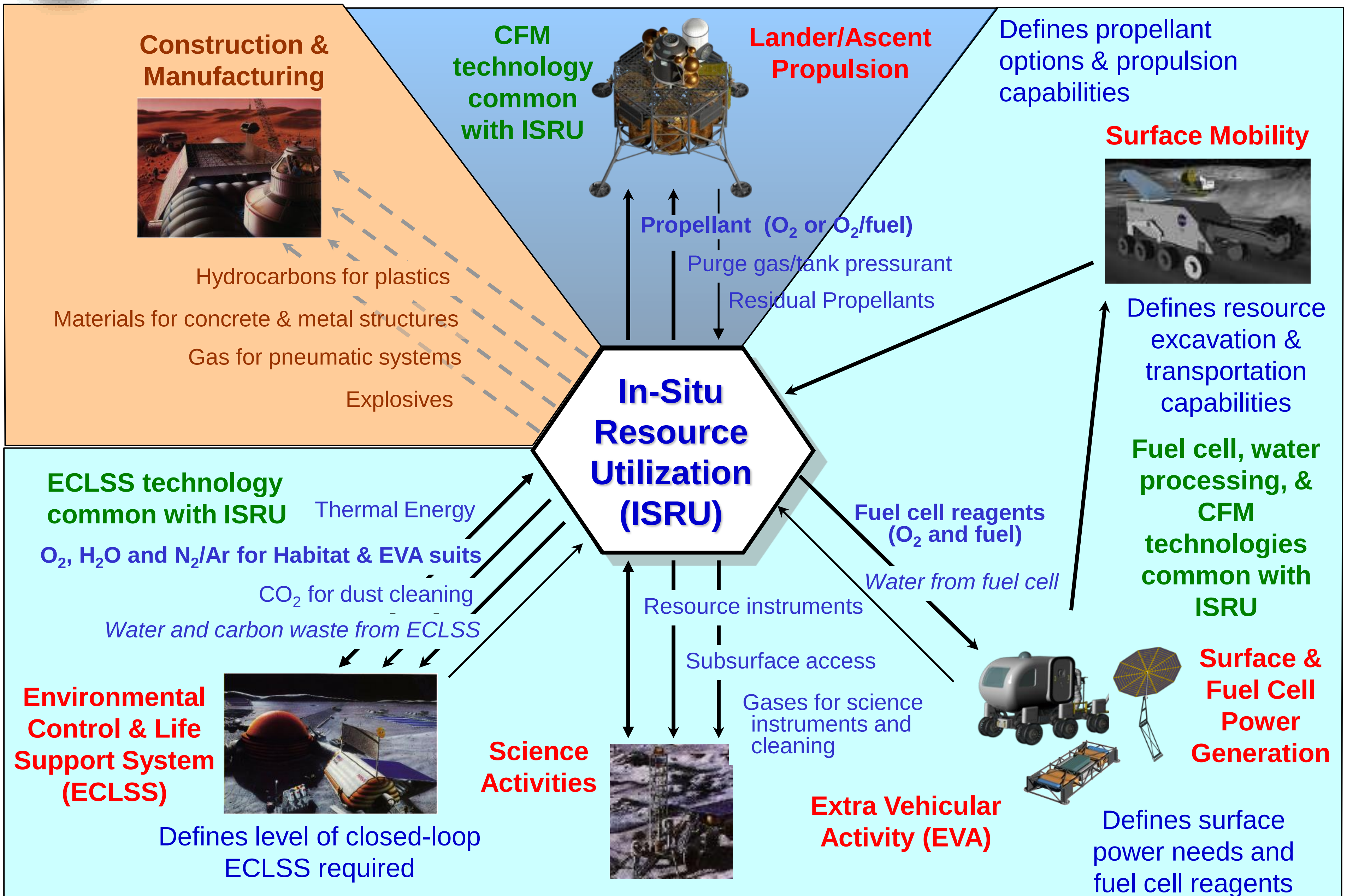
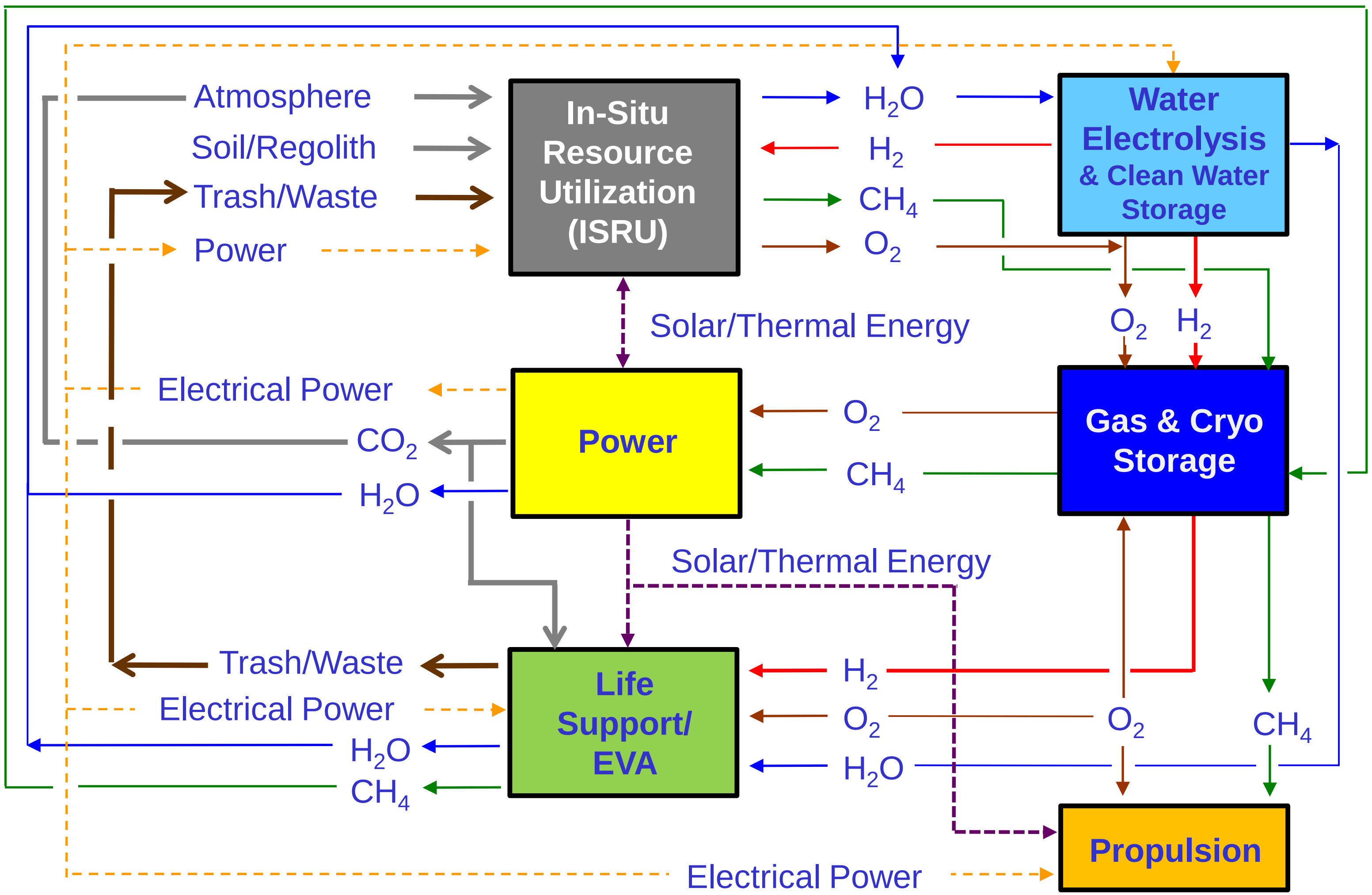
ISRU Strongly Influences Element Designs and Architecture Choices



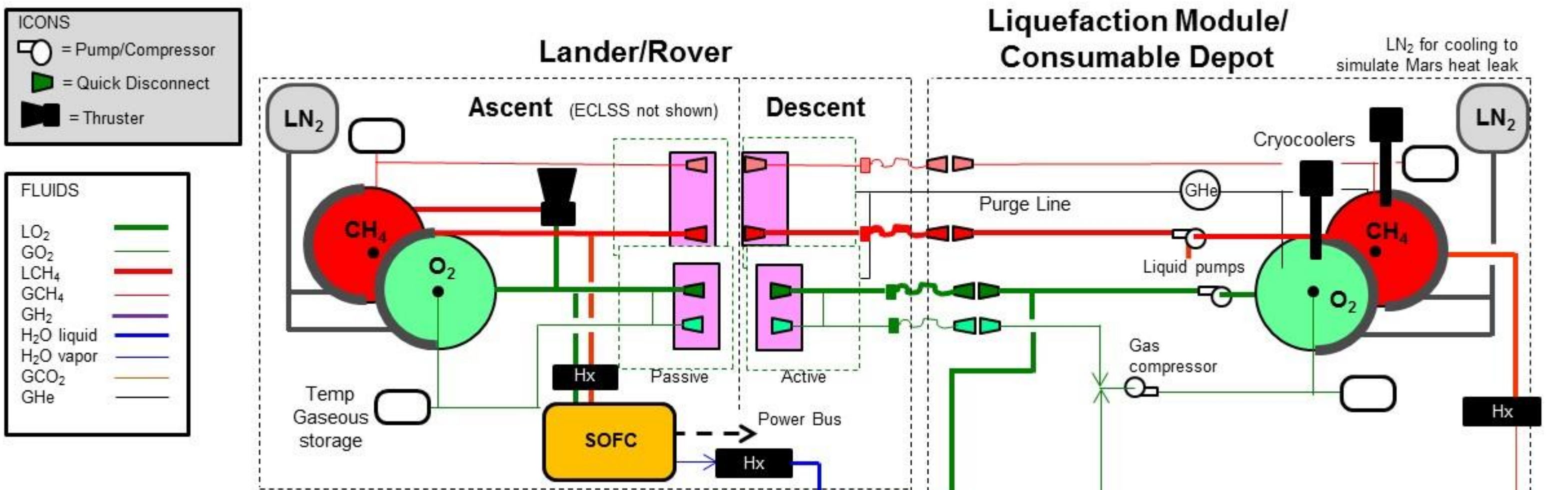
Integrated Fluids & Commodities For Exploration Systems

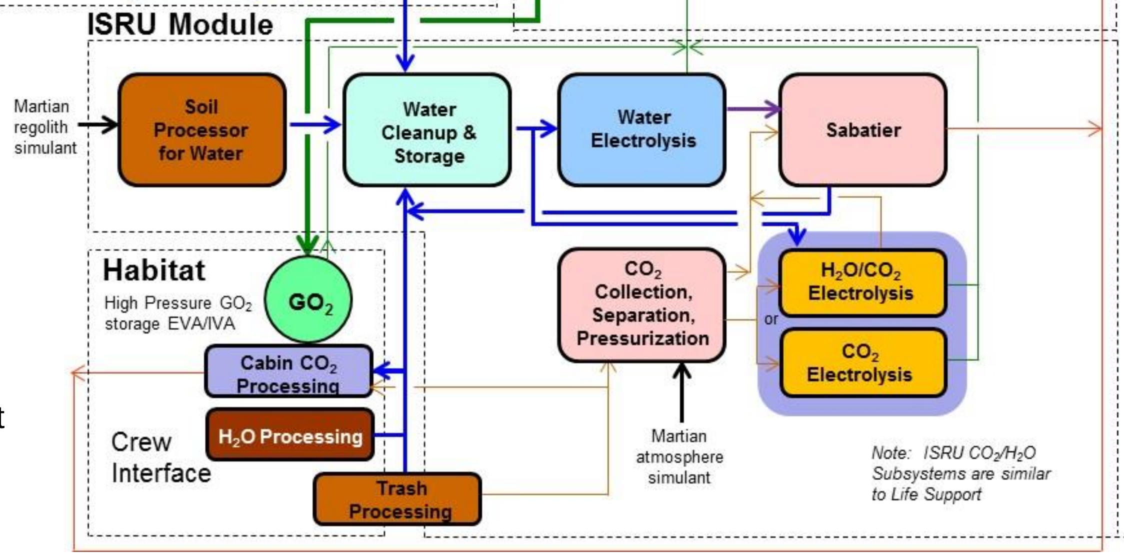
Goal is to 'Close the Loops' Across Multiple Systems

- Identify where common fluids, pressures, quality, and standards *are possible*
  - ➢ Enables common storage, distribution, and interfaces
- Identify where common processes and technologies *are possible*
  - ➢ Enables common hardware for flexibility and reduced DDT&E
  - ➢ Enables modularization of non-unique hardware for multiple systems



Integrated ISRU, Power, Life Support, and Propulsion Systems





Mission Scenarios

1. Utilize residual propellant in descent tanks to operate SOFC
2. Make and store propellants for Mars ascent vehicle -- Continuous up to 480 days
3. Transfer LO_2 and CH_4 to crewed pressurized rover/spacecraft
4. Examine integration of life support with ISRU and/or propellant/fuel cells consumables

It is important that technologies and processes selected and element operations be considered at the architecture level vs optimized for each element

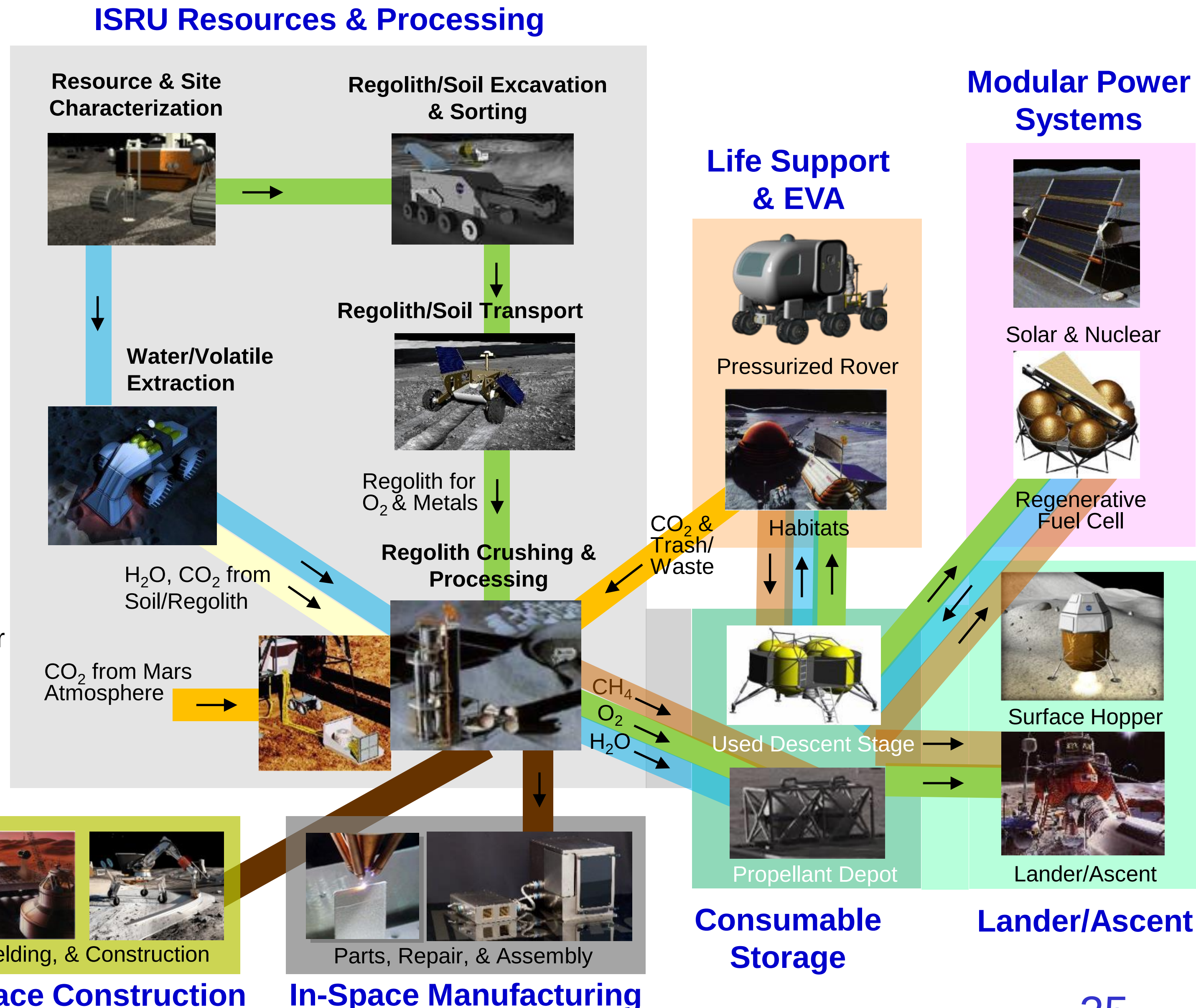
Backup

ISRU Integrated with Exploration Elements
(Mission Consumables)

ISRU Functions/ Elements
- Resource Prospecting
- Excavation
- Regolith Transport
- Regolith Processing

Support Functions /Elements
- Power Generation & Storage
- O_2, H_2, and CH_4 Storage and Transfer

Shared Hardware to Reduce Mass & Cost
- Solar arrays/nuclear reactor
- Water Electrolysis
- Cryogenic Storage
- Mobility



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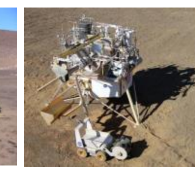
ISRU Examples and Analogies

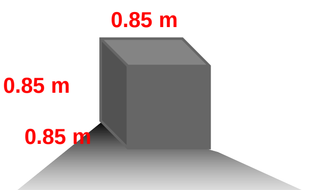
- Excavation rates required for lunar 10 MT O_2/yr production range based on extraction efficiency of process selected and location
  - H_2 reduction at poles (~1% efficiency): 150 kg/hr
  - CH_4 reduction (~14% efficiency): 12 kg/hr
  - Electrowinning (up to 40%): 4 kg/hr
- Excavation rates required for 14.2 MT H_2O/mission production range based on water content
  - Hydrated soil (3%): 41 kg/hr
  - Icy soil (30%): 4 kg/hr

- Cratos & LMA rovers: 10 to 20 kg/bucket at field test in Hawaii
- Robotic excavation competitions:
  - 2009: 437 kg in 30 min.; remote operation
  - 2015: 118 kg in 20 min; autonomous operation
- Soil Processing
  - ROxygen: 5-10 kg/hr
  - PILOT: 4.5-6 kg/hr
  - Pioneer SBIR: 4 kg/hr
  - MISME: 0.2 kg/hr

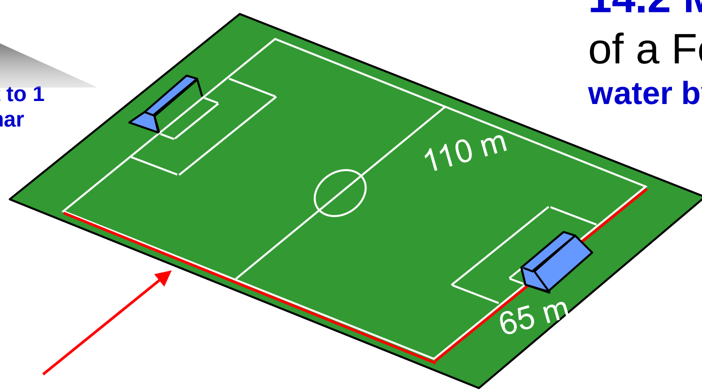






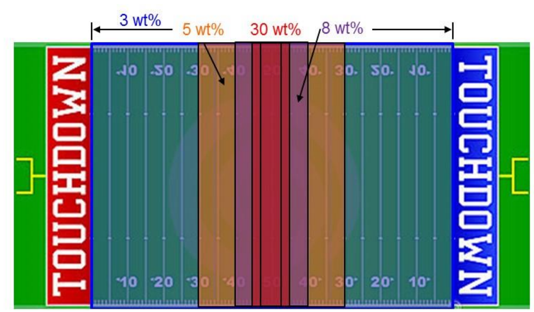


Volume equivalent to 1 Metric Ton of lunar regolith



10 MT of lunar oxygen per year requires excavation of a Soccer field to a depth of **0.6 to 8 cm!** **(14% to 1% efficiencies)**

14.2 MT of Mars water per mission requires excavation of a Football field to a depth of **1.1 to 9.6 cm!** **(30% to 3% water by mass)**



H_2O 1.238 kg/hr, 480 days — Soil 1500 kg/m3, Ice 940 kg/m3

Water wt%	Soil wt%	Water kg	Soil kg	Total kg	Extraction 80%	Ave Density kg/m3	Tot Vol m3	FB Depth cm	FB Field yds
3	97	14261.76	461130.2	475392.0	594240.0	1483.20	400.65	9.58	100.00
5	95	14261.76	270973.4	285235.2	356544.0	1472.00	242.22	5.79	60.46
8	92	14261.76	164010.2	178272.0	222840.0	1455.20	153.13	3.66	38.22
30	70	14261.76	33277.4	47539.2	59424.0	1332.00	44.61	1.07	11.14
70	30	14261.76	6112.2	20373.9	25467.4	1108.00	22.99	0.55	5.74

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Mars mineral resources of interest for ISRU

Resource	Potential Mineral Source	Reference
Water, Hydration/ Hydroxyl	Gypsum – ($CaSO_4.2H_2O$) Jarosite – ($KFe^{3+}{}_3(OH)_6(SO4)_2$) Opal & hydrated silica Phyllosilicates Other hydrated minerals (TBR)	Horgan, et al.(2009), Distribution of hydrated minerals in the north polar region of Mars, J. Geophys. Res., 114, E01005 Mustard et al.(2008), Hydrated silicate minerals on Mars observed by the Mars Reconnaissance Orbiter CRISM instrument, Nature 454, 305-309
Water, Ice	Icy soils Glacial deposits	
Iron*	Hematite Magnetite Laterites Jarosite Triolite Ilmenite	Ming et al. (2006), Geochemical and mineralogical indicators for Aqueous processes in Columbia Hills of Gusev Crater, Mars" JGR 111, E02S12
Aluminum*	Laterites Aluminosilicates Plagioclase Scapolite	
Magnesium*	Mg-sulfates	
Silicon	Pure amorphous silica Hydrated silica Phyllosilicates	Rice et al. (2010), "Silica-rich deposits and hydrated minerals at Gusev Crater, Mars: Vis-NIR spectral characterization and regional mapping" Icarus 205 (2010) 375–395
Titanium*	Ilmenite	

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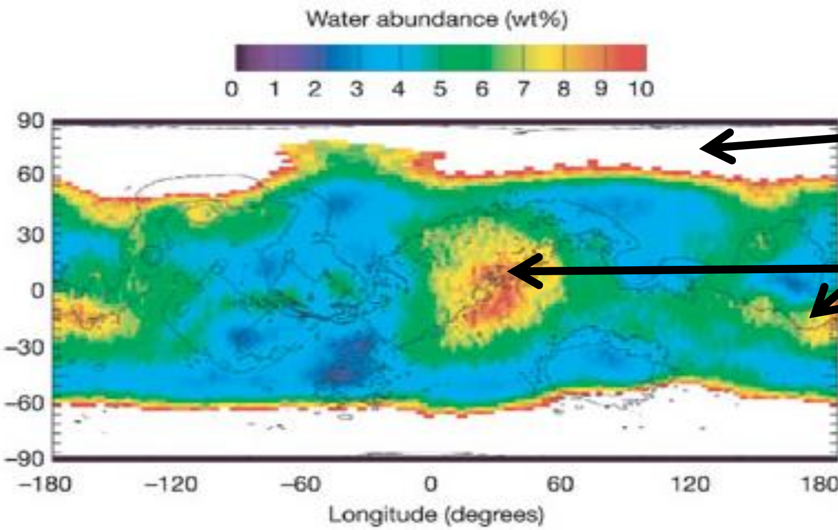
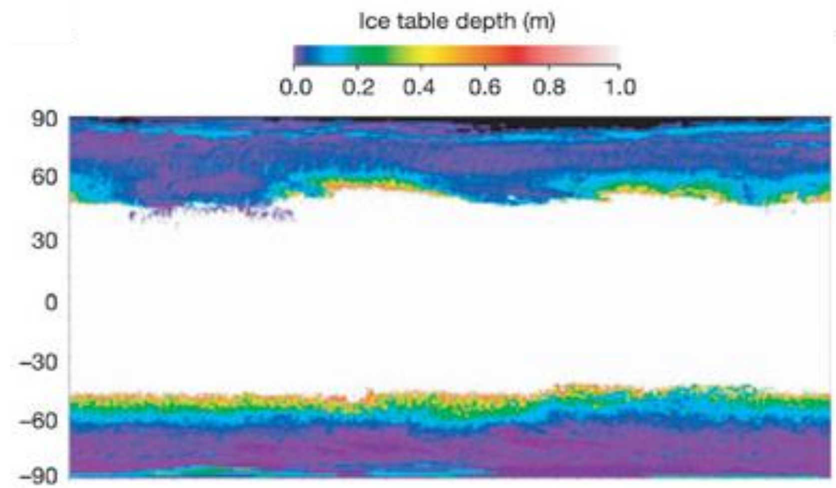
Mars Water Form & Distribution

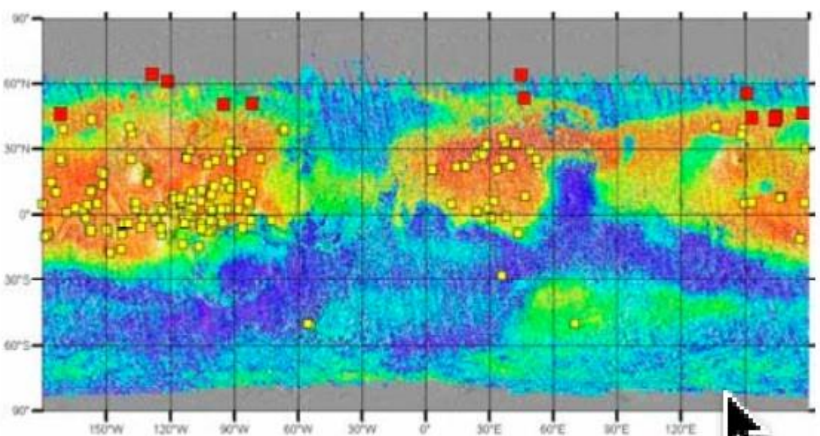


Mid- and high-latitude shallow ice

Thought to be dominated by hydrated minerals

Mid-Latitude Ice-Rich Mantles





New Craters Confirm Shallow, Nearly Pure Ice

- Newly formed craters exposing water ice (red) are a subset of all new craters (yellow). Background color is TES dust index. (Adapted from Byrne et al. (2011) Science)

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Summary of What we Know About Water in "Hydrated Mineral Deposits"

Type of Deposit	General Description	How it has been Modeled Spectrally	Possible water content	Issues
Loose regolith	Powdered rock, salts, amorphous materials	Mix of plagioclase, olivine, pyroxene, npFeOx	4(2-5)% from spectral modeling and direct measurement	Easy to harvest; perchlorate salts may be common
Layered phyllosilicate	Stratified deposits rich in smectite	Mix of up to 50% smectite clays with primary igneous minerals (ol, px. Plag)	9-10% based on spectral modeling and assumed low hydration state of clays	Indurated and competent; more erodible than basalt
Crustal phyllosilicate	Smectite clays in basaltic groundmass	Mix of 5-10% smectite with weakly altered basalt	3-5% based on spectral modeling, examination by Opportunity	Fractured bedrock
Sulfate-bearing layered deposits	Dust + sand with variable content and type of sulfate cement	Mix of sulfate and hematite with Mix of plagioclase, olivine, pyroxene, npFeOx	6-14% from direct measurement of elemental abundances, hydration state from spectral models	Competent but easily erodible by wind; leaves little debris so must be fine-grained
Carbonate-bearing deposits	Olivine partly altered to carbonate	Mixture of olivine basalt and carbonate	7% based on spectral models	Probably very indurated bedrock
Hydrate silica-bearing deposits	Silica with range of hydration mixed w/ basalt	(Assumed: cement in basaltic sediment)	(5% based on assumed composition, could be up to)	Induration and purity probably highly variable

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Water/Volatiles Released from Mars Soil
(SAM instrument: Rocknest sample)

Region 1: <300 C

- 40-50% of the water released
- Minimal release of HCl or H_2S

Region 2: <450 C

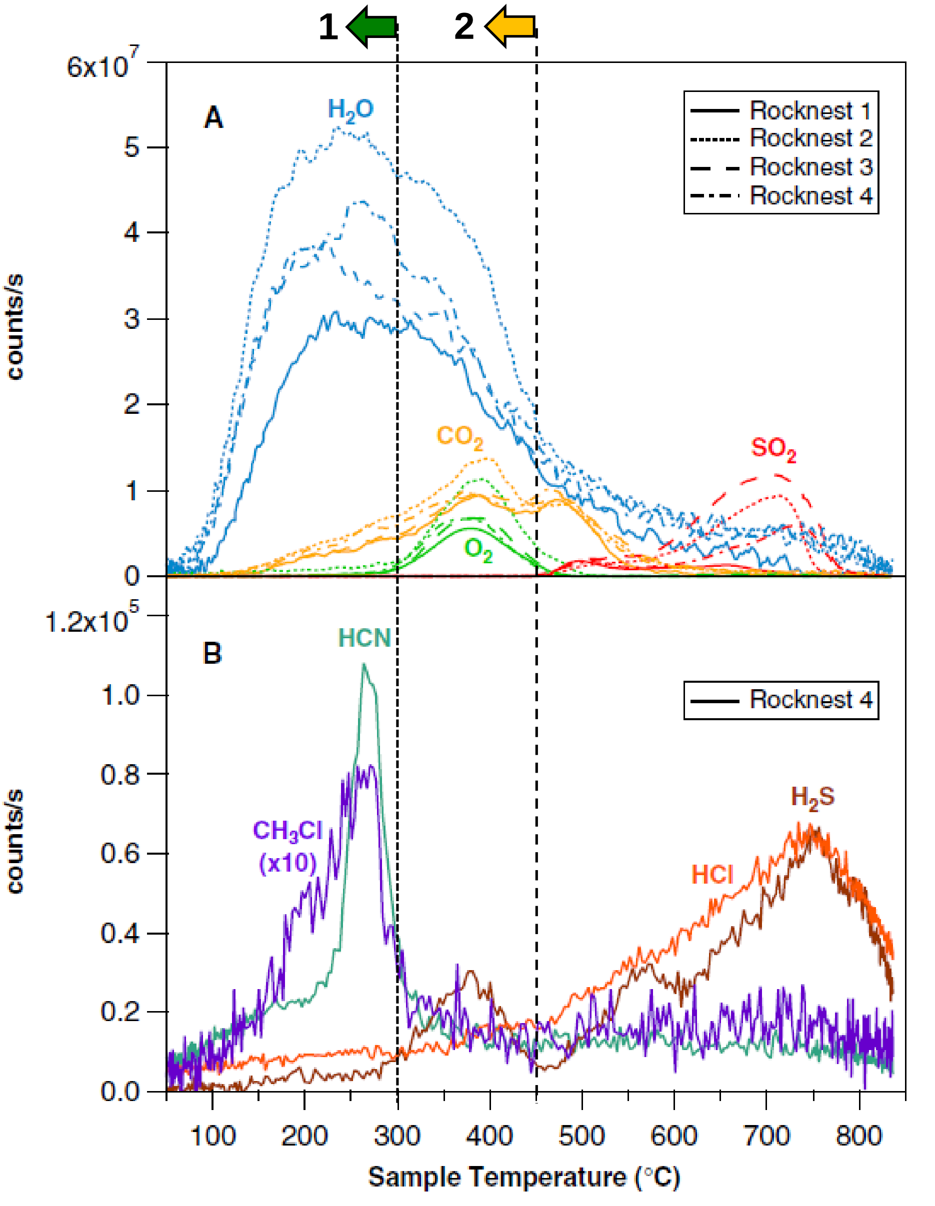
- >80% of the water released
- CO_2 and O_2 released from decomposition of perchlorates
- Some release of HCl or H_2S but before significant amounts are release

Predicted Volatile Release Based on Lab Experiments

CO_2 released by
1. Absorbed atmosphere <200C
2. Oxidation of organic material >200 C
3. Thermal decomposition of carbonates >450 C

O_2 released by
1. Dehydroxylation of clays <350 C
2. Decomposition of non-metal and metal oxides >500 C

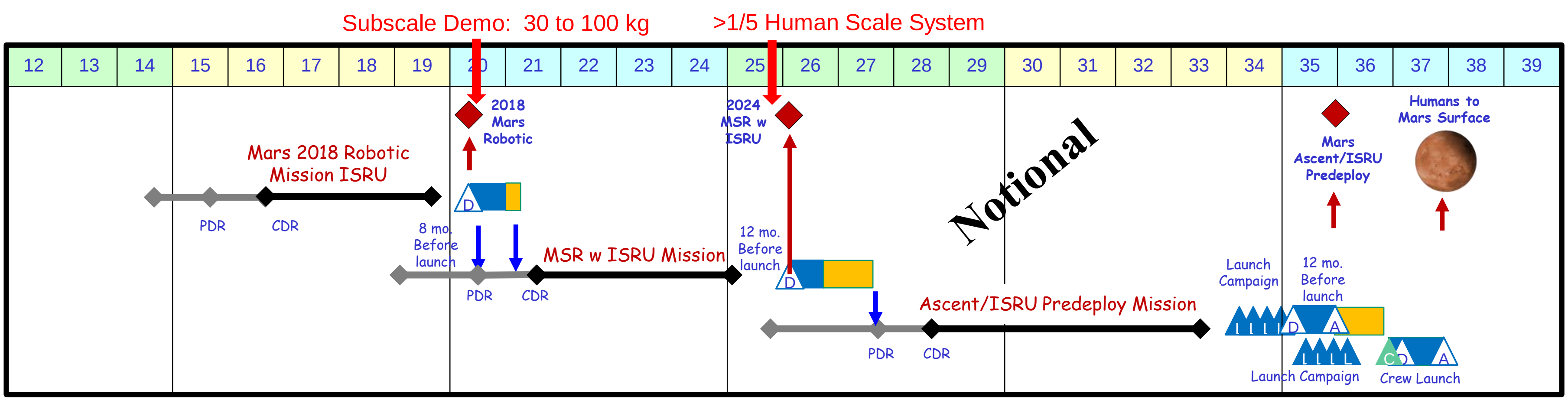
CH_3Cl and CH_2Cl_2 released by
1. Decomposition of $Mg(ClO_4)_2$ perchlorate >200C



Need for Early ISRU Demonstration (2020)

- **Resource uncertainty and environmental impact on ISRU processes are the greatest risks for ISRU implementation:**
  - Water (hydration and ice) resources have significant interest for science, search for life, and ISRU.
  - Dust content, concentration, size/shape distribution at surface are extremely important for long-term operation
  - ➢ Joint Science/Exploration mission examining soil/water, dust, atmosphere, and impact on critical ISRU systems provide synergistic goals/objectives

- **To Minimize Risk, sequential development and demonstration approach recommended where lessons-learned flow into next effort before PDR/CDR**



➢ **Need to start now for human mission to Mars by end of 2030's**

ISRU Processes Affected by Mars Environment & Resource Characteristics

Mission Environment	ISRU Process	Potential Impacts/Effects
Surface regolith properties (fines & bulk)	Excavation and Material Transfer	Could reduce efficiency of regolith excavation and material transfer due to: • Adhesion of particles/grains • Compactness • Water/ice content
	Soil Processing unit Inlet/Outlet	Could cause sealing problems for multiple cycle processing
	Water Filtration & Cleanup	Fines in soil could reduce performance of water cleanup and processing
Dust property uncertainties • Particle size/shape distribution • Local dust amount • Dust particle deposition rate • Dust mineral composition	Filter Design	Could reduce CO_2 acquisition due to: • Improper micron size level required to filter dust • Change in flow rate/Delta P across filter • Improper dust holding capacity or regeneration capability
	Chemical Reactors	Could cause reduced performance or failure due to dust poisoning catalysts and electro-chemical/thermal reactors
	Radiators & Thermal Control	Could cause insufficient heat rejection or increased thermal power demand at night due to: • Change in surface emissivity • Change in heat transfer coefficient
	Solar Power	Could cause insufficient power or oversized array to handle degradation over time • Dust coating and abrasion could reduce cell efficiency • Deployment and sun tracking mechanism binding from dust
	Mobility/Excavation	Could cause reduced performance or failure due to dust intrusion into rotating mechanisms
	Control Electronics	Could cause arching, grounding, and electrostatic discharge
Solar/thermal conditions based on: • Landing site elevation • Landing latitude • Day/night cycles	Solar Power	Could cause insufficient power or oversized array to handle degradation over time • Temperature cycles and UV radiation degraded cells • Structure and deployment mechanisms need to withstand dust/wind loads
	Radiators & Thermal Control	Radiator/thermal control system must be sized to surface and sky temperatures, and solar flux/angle on incidence
Atmospheric conditions based on: • Landing site elevation • Annual pressure/temperature cycle • Day/night cycles • Atmospheric constituents & concentration	Atmosphere Collection	Adsorption beds, pumps, and separation units must be sized to CO2 partial pressure
	Control Electronics	Low pressure atmosphere could cause arching, grounding, and electrostatic discharge for high voltage applications
	Chemical Reactors	Atmospheric constituents/impurities could reduce performance or failure due to poisoning catalysts and electro-chemical/thermal reactors

Space Resource Challenges

- **What resources exist that can be used?**
  - Oxygen and metals from regolith/soils
  - Water/Ice
  - Atmospheres & volatiles
  - Thermal environments
  - Sunlight
  - Shielding: Lava tubes, regolith, water, hills/craters
- **What are the Uncertainties associated with the Resources?**
  - Polar volatiles:
    - **Where is it**, What is there, how is it distributed, terrain and environment, contaminants?
  - Mars water/ice in soil
    - What form is the water (ice, mineral-bound), how is it distributed, terrain and environment, contaminants?
  - Near Earth Objects/Asteroids/Mars Moons
    - What is there, how is it distributed, environment, contaminants
    - Ability to revisit NEO of interest (time between missions)
    - What techniques are required for micro-g mining and material processing?

ISRU Technical Challenges

- **Is it Technically feasible to collect, extract, and process the Resource?**
  - Energy: Amount and type (especially for polar resources in shadowed regions)
  - Life, maintenance, performance
  - Amount of new technology required

- **Long-duration, autonomous operation**
  - Autonomous control & failure recovery
  - No crew for maintenance; Non-continuous monitoring from Earth

- **High reliability and minimum (zero) maintenance**
  - No (or minimal) maintenance capability for pre-deployed and robotic mission applications
  - Networking/processing strategies (idle redundancy vs over-production/degraded performance)
  - Develop highly reliable thermal/mechanical cycle units (valves, pumps, heat exchangers, etc.)
  - Develop highly reliable, autonomous calibration control hardware (sensors, flowmeters, etc.)

- **Operation in severe environments**
  - Efficient excavation of resources in dusty/abrasive environments
  - Methods to mitigate dust/filtration for Mars atmospheric processing
  - Micro-g environment for asteroids and Phobos/Deimos

- **Integration and Operation with other Exploration Systems**
  - Exploration systems must be designed to utilize ISRU provided products; may cause selection of different technologies/approaches

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Mars ISRU Challenges

- **Resource Unknowns**
  - Atmosphere resource unknowns: i) size distribution, number of particles, and dust type near surface
  - Water resource unknowns: No single form of water resource
    - Hydrated mineral/soil unknowns: i) Water content in soil as a function of location, depth, and soil type; ii) hydrated mineral/soil physical characteristics for excavation and transfer; iii) contaminants released during evolution and collection of water from hydrated minerals/soil
    - Subsurface ice unknowns: i) Ice content in soil as a function of location, depth, and soil type; ii) soil/ice physical characteristics for drilling and transfer; iii) contaminants released during evolution and collection of water from icy soils

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  - Autonomous control & failure recovery
  - No crew for maintenance; Non-continuous monitoring from Earth

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Core ISRU Technologies Are Applicable To Both Moon and Mars

Lunar & Mars ISRU Share Many Common Technologies & Modules

Lunar ISRU		*Core Technologies*		Mars ISRU
• Site preparation • Oxygen extraction	←	• Soil excavation and transfer	→ (with Water extraction from soil/solid material and Water Distillation/Cleanup)	• Water extraction from soil
• Water & volatile extraction	← (with Water Distillation/Cleanup)	• Water extraction from soil/solid material		
		• Water Distillation/Cleanup		
• Pneumatic excavation	←	• CO_2 & N_2 Acquisition & Separation	→	• **Mars atmosphere resource collection and conditioning**
• **Methane regeneration for carbothermal reduction**	← (with Methane Reforming)	• Sabatier Reactor	→	• **Fuel production**
		• Methane Reforming	→ (with RWGS Reactor and CO_2 Electrolysis)	• **Oxygen production**
• **Crew waste/trash processing**	← (with CO_2 Electrolysis)	• RWGS Reactor		
		• CO_2 Electrolysis		
• Water electrolysis	← (with H_2O Electrolysis and H_2O Storage)	• H_2O Separators	→ (with H_2O Electrolysis and H_2O Storage)	• Water electrolysis
		• H_2O Electrolysis		
		• H_2O Storage		
• All processing systems	←	• Heat Exchangers	→	• All processing systems
• All oxygen storage and transfer systems	← (with the three items below)	• Liquid Vaporizers	→ (with the three items below)	• All oxygen storage and transfer systems (Note: Mars atmosphere does not allow for MLI usage)
		• O_2 & Fuel Storage (0-g & reduced-g)		
		• O_2 Feed & Transfer Lines		
		• O_2/Fuel Couplings		

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ISRU Shares Common Technologies with Other Mission Elements

ISRU Maximizes Benefits, Flexibility, & Affordability

- Modular hardware & common mission fluids reduced logistics, increases reliability & flexibility, and reduces development and mission costs

In-Situ Production Of Consumables for Propulsion, Power, & ECLSS

Fuel Cell Power for Spacecraft, Rovers & EVA

H_2O -> H_2/O_2

0-g & Surface Propellant Depots

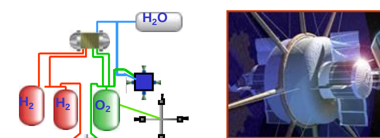
Core Technologies

- Soil Excavation and Transfer
- Water extraction from Soil/Solid Material
- Water Distillation/Cleaning
- CO_2 & N_2 Acquisition & Separation
- Sabatier Reactor
- RWGS Reactor
- CO_2 Electrolysis
- Methane Reforming
- H_2O Separators
- H_2O Electrolysis
- Fuel Cells
- H_2O Storage
- Heat Exchangers
- Liquid Vaporizers
- O_2 & Fuel Storage (0-g & reduced-g)
- O_2 Feed & Transfer Lines
- O_2/Fuel Couplings
- O_2/Fuel Igniters & Thrusters

Life Support Systems for Habitats & EVA

Habitat, EVA, and radiation shielding

Water – Gaseous H_2/O_2 Based Propulsion



Station keeping, depots, integrated power

Non-Toxic O_2-Based Propulsion

Launch vehicle & human/robotic landers

Difference between Mars ISRU & Life Support

ISRU		Life Support
Resource Feedstock		
Potentially unlimited (except for Trash)		Controlled feedstock as function of number of crew
<100% collection efficiency acceptable		Maximize collection efficiency
Feedstock input ratios function of resource availability		Feedstock input rations function of crew waste products
Processing Systems		
External to habitable volumes		Internal to habitable volumes
Pressures and temperatures are a function of optimizing chemical reaction and system mass/power		Pressures based on cabin pressure; temperatures minimized for thermal control and touch
Carbon dioxide/Carbon monoxide (CO_2/CO) processing reactors run hydrogen rich with H_2 recycling to maximize CO_2/CO conversion		CO_2 processing reactors run hydrogen poor to mitigate H_2 leakage concerns
Production and venting of CO allowed		Production of CO avoided due to toxicity risk
System Design		
CO_2 Acquisition, CO_2 Processing, & H_2O Processing highly integrated (esp. thermally)		Subsystems for ISS were designed and built seperately
Subsystems designed to operate all at the same time. Separate subsystem operation or batch process a function of available power or CO_2 collection approach.		Subsystems for ISS operate at same or different times
Small amount of leakage acceptable		Leakage not acceptable because of habitable volume concerns
Oxygen Storage		
Storage pressure optimized for system performance and liquefaction energy		Storage pressure for EVA portable life support system recharge
Oxygen purity based on end user (propulsion, fuel cell, or life support		Oxygen purity based on crew
Operation		
Operate continuously while power is available (sunlight or nuclear); minimize start-up/shutdown operations		Operate on as needed basis. Continuous if possible
ISRU systems must be designed for minimum/no maintanace since operations often occur before crew arrives		Crew maintanance acceptable

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ISRU Influences other Exploration Systems

- **Integration and Operation with other Exploration Systems is critical**
  - Early integrated ground development activities required to foster interaction

System Maturation Teams	Dependancies		
	Required From	Delivered To	Shared Areas of Interest
EVA	Maintance and repair	Consumables (quality, type, amount)	CO_2 and water management
Human Robotic Mission Ops	Mobility, Manipulation	Requirements for mobility & manipulation	End effectors for civil engineering
Crew Health & Protection	Requirements for radiation shielding	Approaches for radiation shielding	Radiation material effectiveness testing
Autonomous Mission Ops	Autonomy, failure tolerance	Requirements	System and analog testing; precursors
Communication & Navigation	Comm and nav.	Requirements	Comm time delay operations
ECLSS & Env. Monitoring	Trash and waste feedstock	Consumables (quality, type, amount)	CO_2, water, and trash mgmt and processing
Entry, Descent, and Landing	Landing accuracy for resource assessment Plume exhaust interaction with surface	Aeroshell from space resources Landing pads/berms	Plume modeling & mitigation testing
Power & Energy Storage	Electrical (and thermal) energy	Fuel cell consumables. Energy generation & storage from in-situ materials	Fuel cell reactant regeneration; solid oxide fuel cells and water electrolzers
Radiation	Requirements for radiation shielding	Approaches for radiation shielding	Radiation material effectiveness testing
Thermal (incl. Cryo Fluid Management)	Consumable liquefaction, storage, transfer; thermal management in shadowed regions	Requirements; Waste heat; in-situ thermal storage approaches	Lunar night and polar region survival and/or operation
SKG Measurement Instruments & Sensors	Instruments/Data for Resource Assessment	Instruments/Data for Resource Assessment	Search for water and volatiles
Fire Safety			Hazard mitigation and sensors
Propulsion	Requirements for propellants	Consumables (quality, type, amount)	Propulsion, storage, and transfer testing
ISRU			

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MARCO POLO Mars Atmosphere/Soil ISRU

MARCO POLO (Mars Atmospheric & Regolith COllector/PrOcessor for Lander Operations) is a combined Mars ISRU atmosphere & soil processing demonstration which includes a rover for excavation and science/prospecting.

Atm. Processing Module:
- CO_2 capture using freezing
- Sabatier converts H_2 and CO_2 into Methane and water

Soil Processing Module:
- Soil Hopper handles 30kg
- Soil dryer uses sweep gas and <500 deg C to extract water

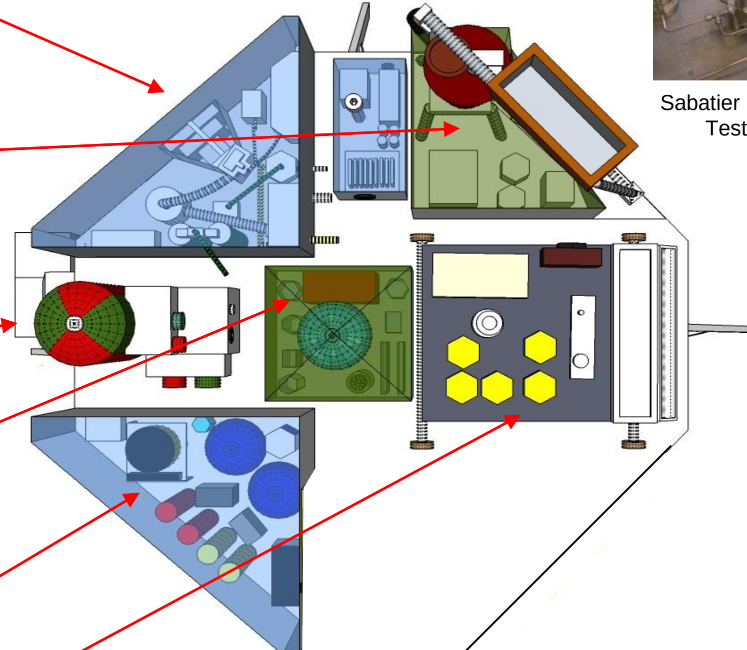
Liquefaction Module:
- Common bulkhead tank for Methane and Oxygen liquid storage

Water Cleanup Module:
- Cleans water prior to electrolysis
- Provides clean water storage

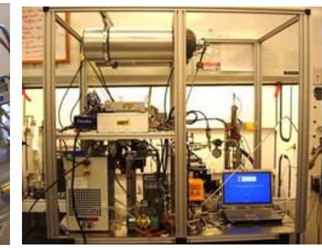
Water Processing Module:
- Electrolyze water into H_2 & O_2

Excavator/Science Rover
- Collects soil for processing
- Can include science instruments

Notional Mars Surveyor Lander scale lander



Sabatier Reactor Testing



Atmosphere Processing Module

Regen. Water Cleanup

Soil Processing

Water Processing Module

Notional MARCO POLO Design Characteristics
- Nom. Mission Life = 90 Mars days (sols)
- Mass = 200+ kg
- Dimensions = Modular; fit on top of 3 m diameter lander
- Ave. Power; >2000 W
- Production = Up to 0.5 kg O_2/hr

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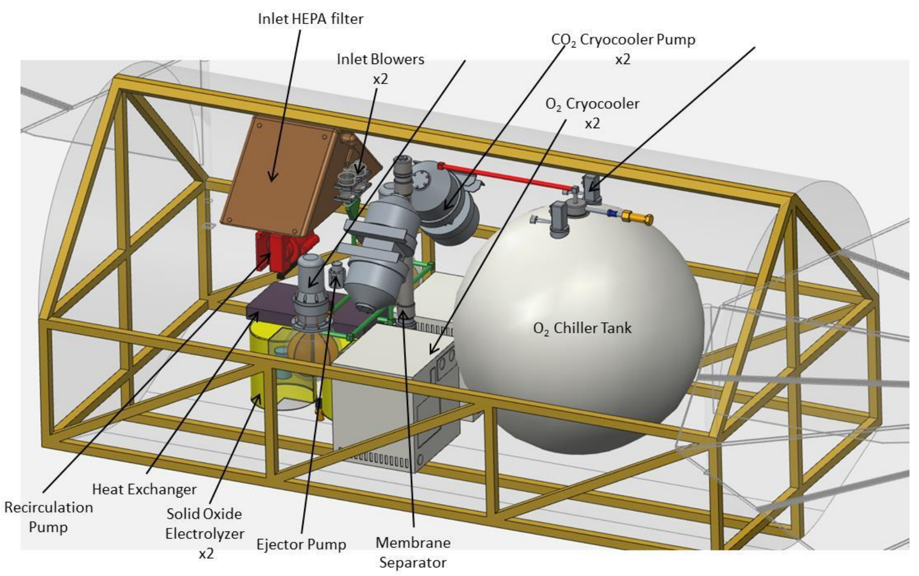
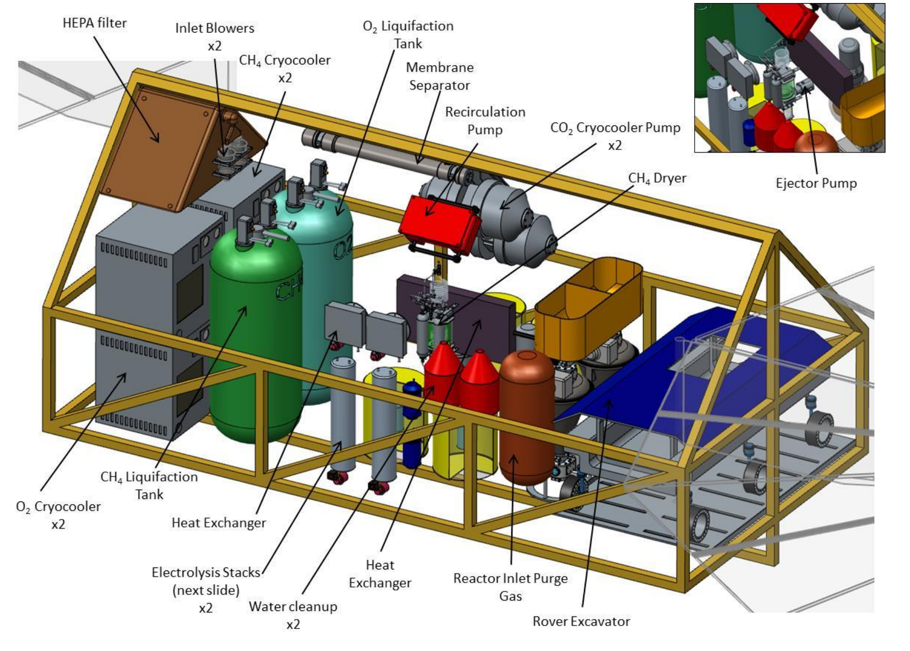
Mars ISRU Pathfinder Demo Payload Options

- **Mars Atmosphere Processing (O_2 only)**
  - Electrostatic precipitator w/ regenerative HEPA filter
  - CO_2 collection (freezing)
  - CO_2 processing: Solid Oxide Electrolysis
  - CO/CO_2 separation and recycling to increase performance
  - O_2 liquefaction
  - O_2 storage



- **Mars Atm/Soil Processing (O_2/CH_4)**
  - Electrostatic precipitator w/ regenerative HEPA filter
  - CO_2 collection (freezing)
  - CO_2 processing: Sabatier Reactor
  - Rover/Excavation
  - Soil processing reactor (up to 450 C)
  - Water separation/cleanup module
  - Water electrolysis (Cathode Feed PEM)
  - O_2 & CH_4 product dryer
  - O_2 & CH_4 liquefaction & Storage



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ISRU Demo Payload Results Summary

Mars Atm ISRU Demo

O_2 Production rate: 0.45 kg/hr	Mass (kg)	Power (KW)
Filtration	1.23	0.00025
CO_2 Collection/Freezer	173	2.23
SOE Processor	5.6	3.7
SOE Recirculation system	34.6	0.187
O_2 Liquefaction and Storage	70	0.6
Secondary Structure (15%)	42.7	
Solar Arrays (2)	45	
Power conditioning/batteries*	TBD	TBD
Thermal Management/Radiators	TBD	TBD
Total	372.1	6.72

Mars Soil ISRU Demo

O_2 Production rate: 0.48 kg/hr	Mass (kg)	Power (KW)
Rover Excavator**	170	
Soil Processor & Water Cleanup	193	3.1
Water Electrolysis (2)	40	2.8
O_2 Dryer	4.1	0.064
O_2 Liquefaction and Storage	72	0.7
Secondary Structure (15%)	71.9	
Solar Arrays (2)	45	
Power conditioning/batteries*	TBD	TBD
Thermal Management/Radiators	TBD	TBD
Total	596.0	6.66

Combined Atm/Soil ISRU Demo

CH_4: 0.12 kg/hr

O_2 Production rate: 0.48 kg/hr;	Mass (kg)	Power (KW)
Filtration	1.3	0.00025
CO_2 Collection/Freezer	43	0.574
Sabatier Microchannel Reactor	1	0.082
Rover Excavator**	170	
Soil Processor & Water Separation	193	1.7
Water Capture/Temp Storage	3.7	0.5
Water Electrolysis (2)	40	2.8
O_2 and CH_4 Dryers	5	0.098
O_2 Liquefaction and Storage	72	0.7
CH_4 Liquefaction and Storage	58	0.42
Secondary Structure (15%)	88.1	
Solar Arrays (2)	45	
Power conditioning/batteries*	TBD	TBD
Thermal Management/Radiators	TBD	TBD
Total	720.1	6.9

Rover oversized for mission

ISRU Plant Only

	Atm	Soil	Combined
Mass (kg)	246.59	272.67	330.05
Power (KW)	6.12	5.96	5.75

Rover not included

Human mission would include 3 units

*Mass and power available for batteries
**Rover not optimized for soil excavation or production rate

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Propellant Storage vs Location in Space

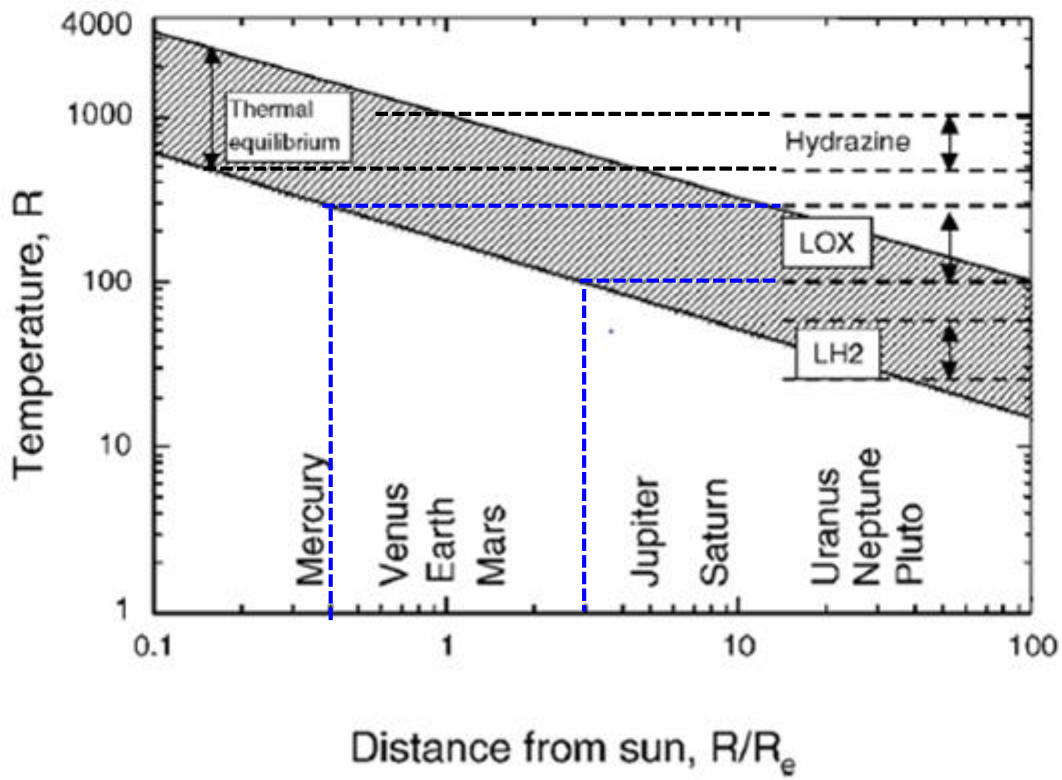

Fig. 9 Equilibrium temperature in space;[71] limits of thermal equilibrium depend on insulation, absorptivity/emissivity, etc.

Oxygen and Methane are 'space' storage (i.e. heating or cooling is minimal to maintain its state) for the Earth, Moon, and Mars

[71] **Liquid Fuels and Propellants for Aerospace Propulsion: 1903–2003**, Tim Edwards, *U.S. Air Force Research Laboratory,Wright–Patterson Air Force Base, Ohio 45433-7103*